Wyoming State Geological Survey
Thomas A. Drean, Director and State Geologist

Platte River Basin Water Plan Update
Groundwater Study
Level I (2009 – 2013)

Available Groundwater Determination Technical Memorandum

by

Paul Taucher, Timothy T. Bartos, Karl G. Taboga, Laura L. Hallberg, Melanie L. Clark, James Stafford, Tomas Gracias, Bern Hinckley, Brett Worman, Keith Clarey, Lisa Lindemann, Scott A. Quillinan, Dave Copeland, Richard Hays, Melissa Thompson

Karl G. Taboga, Editor

Prepared for Wyoming Water Development Commission

Laramie, Wyoming
2013

Director and State Geologist Thomas A. Drean

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Editing by:
Karl G. Taboga
Design and layout by:
Brendon Orr

Wyoming State Geological Survey

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Cover photo: North Platte River below Seminoe Dam, Wyoming. Precambrian granitic outcrops of Seminoe Mountains shown in the background. Photo by James Stafford (2010).

Available Groundwater Determination

Technical Memorandum

WWDC Platte River Basin Water Plan Update

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Level 1 (2009 – 2013)

December 2013

Paul Taucher[3], Timothy T. Bartos[2], Karl G. Taboga[1], Laura L. Hallberg[2], Melanie L. Clark[2], James Stafford[1], Tomas Gracias[1], Bern Hinckley[4], Brett Worman[1], Keith Clarey[5], Lisa Lindemann[6], Scott A. Quillinan[7], Dave Copeland[1], Richard Hays[1], Melissa Thompson[1]

Karl G. Taboga[1], Editor

This report was prepared under contract for the Wyoming Water Development Commission (WWDC)5 by the Wyoming State Geological Survey (WSGS)1, the United States Geological Survey (USGS)2, and the Water Resources Data System (WRDS)in cooperation with the Wyoming State Engineer's Office (WSEO) and the Wyoming Oil and Gas Commission WOGCC).

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[1]Wyoming State Geologic Survey, P.O. Box 1347, Laramie, Wyoming, 82073-1347
[2]U.S. Geological Survey, Wyoming Water Science Center, 21 Progress Circle, Suite 6, Cheyenne, Wyoming, 82007
[3]Energy Compliance LLC, 2302 Nighthawk Drive, Laramie, Wyoming, 82070
[4]Hinckley Consulting, 419 S. 5th Street, Laramie, Wyoming, 82070
[5]Wyoming Water Development Commission, 6920 Yellowtail Road, Cheyenne, Wyoming, 82002
[6]Wyoming State Engineer's Office, Herschler Building. Cheyenne, Wyoming, 82002
[7] University of Wyoming, Carbon Management Institute, 2020 Grand Avenue, Suite 500, Laramie Wyoming, 82070

Errata

The following items were replaced in the digital version of this report.

Page 4-34; Figure 4-3. Geologic cross section B-B'B."
Updated version includes labels on diagram.

Page 445; Appendix C. GIS Dataset Sources for Plates and Figures. *Updated version includes figure numbers.*

Page 465; Appendix E. Summary Statistics for Environmental Water Samples, Various Sites In Platte River Basin. *Updated version includes complete appendix.*

Page 541; Appendix F. Summary Statistics for Produced Water Samples, Various Sites in Platte River Basin. *Updated version includes complete appendix.*

Page 565; Appendix G. Trilinear Diagrams for Environmental Groundwater Samples, Varies Sites in Platte River Basin. *Updated version includes complete appendix.*

Page 575; Appendix H. Trilinear Diagrams for Produced Groundwater Samples, Various Sites in Platte River Basin. *Updated version includes complete appendix.*

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Chapter 1

Introduction

Paul Taucher and Karl Taboga

The Wyoming State Engineer's Office (SEO) published the first State Framework Water Plan in 1973 under the Wyoming Water Planning Program (1973). The publication presented a framework plan for the entire state of Wyoming and included summary water plans for each of the state's seven major river drainages. In 1975, the Wyoming Legislature established the Wyoming Water Development Commission (WWDC) and Wyoming Water Development Office (WWDO) to coordinate planning, development and project management efforts for the state's water and related land resources. Between 1979 and 1995, the WWDO completed several major river basin planning studies.

The development of the present State Water Planning Process began in 1997 when the state Legislature directed WWDC to conduct a water planning feasibility study in collaboration with the University of Wyoming (UW) and the SEO that included public input and compilation of a statewide water data inventory. Based on the feasibility study, the Legislature accepted the recommended planning framework and funded the Statewide Water Planning Process in 1999 to update the original 1973 State Framework Water Plan, and specifically to:

- inventory the state's water resources and related lands,
- summarize the state's present water uses and project future water needs,
- identify alternatives to meet projected future water needs, and
- provide water resource planning direction to the state of Wyoming for a 30-year time-frame.

The Wyoming Framework Water Plan (WWC Engineering, and others, 2007a) summarized the separate water plans for Wyoming's seven major river basins **(Figure 1-1)** compiled between 2001 and 2006. The Platte River Basin plan (Trihydro Corporation and others, 2006a, 2006c; Trihydro Corporation, 2006b) summarized technical memoranda on its water resources and use, including the initial Available Groundwater Determination for the Platte River Basin (Lidstone and Associates, 2005b). This Available Groundwater Determination updates, revises, and expands the 2005 Technical Memorandum with a new compilation of available information and represents the most current assessment of the groundwater resources of the Platte River Basin. The data contained in this memorandum is a compilation of existing data obtained by several state and federal agencies. While original maps and tables were developed, and existing maps and tables were updated and modified, no original investigations or research were conducted for this memorandum.

The format of this update follows the general layout of recently completed groundwater determination updates co-authored by the Wyoming State Geological Survey (WSGS) and U.S. Geological Survey (USGS) for the Wind/Bighorn River Basin (Taucher and others, 2012) and Green River Basin (Clarey and others, 2010); much of the content of these two previous studies is found in this memorandum, frequently without citation.

1.1 Interagency agreement and scope

The WWDC and the Wyoming State Geological Survey (WSGS) entered into an Interagency Agreement in June 2009 to review and compile existing information, to update the 2005 Available Groundwater Determination Technical Memorandum. A downloadable file containing the 2005 Memorandum is available online at the WWDC website at http://waterplan.state.wy.us/plan/platte/techmemos/techmemos.html. The Agreement outlined the following tasks for this update of the Platte River Basin Available Groundwater Determination:

- **Identify the major (most widely used) aquifers in the Platte River Basin.** To make this determination the U.S. Geological Survey (USGS) defined all of the aquifers and confining units in geologically distinct areas of the Platte River Basin and presented the information on hydrostratigraphic nomenclature charts **(Plates J, K, M, S, T,** and **U**; **Figure 7-2).** Based on these detailed analyses, the digital Geographic Information System (GIS) geologic units mapped on **Plate 1** and

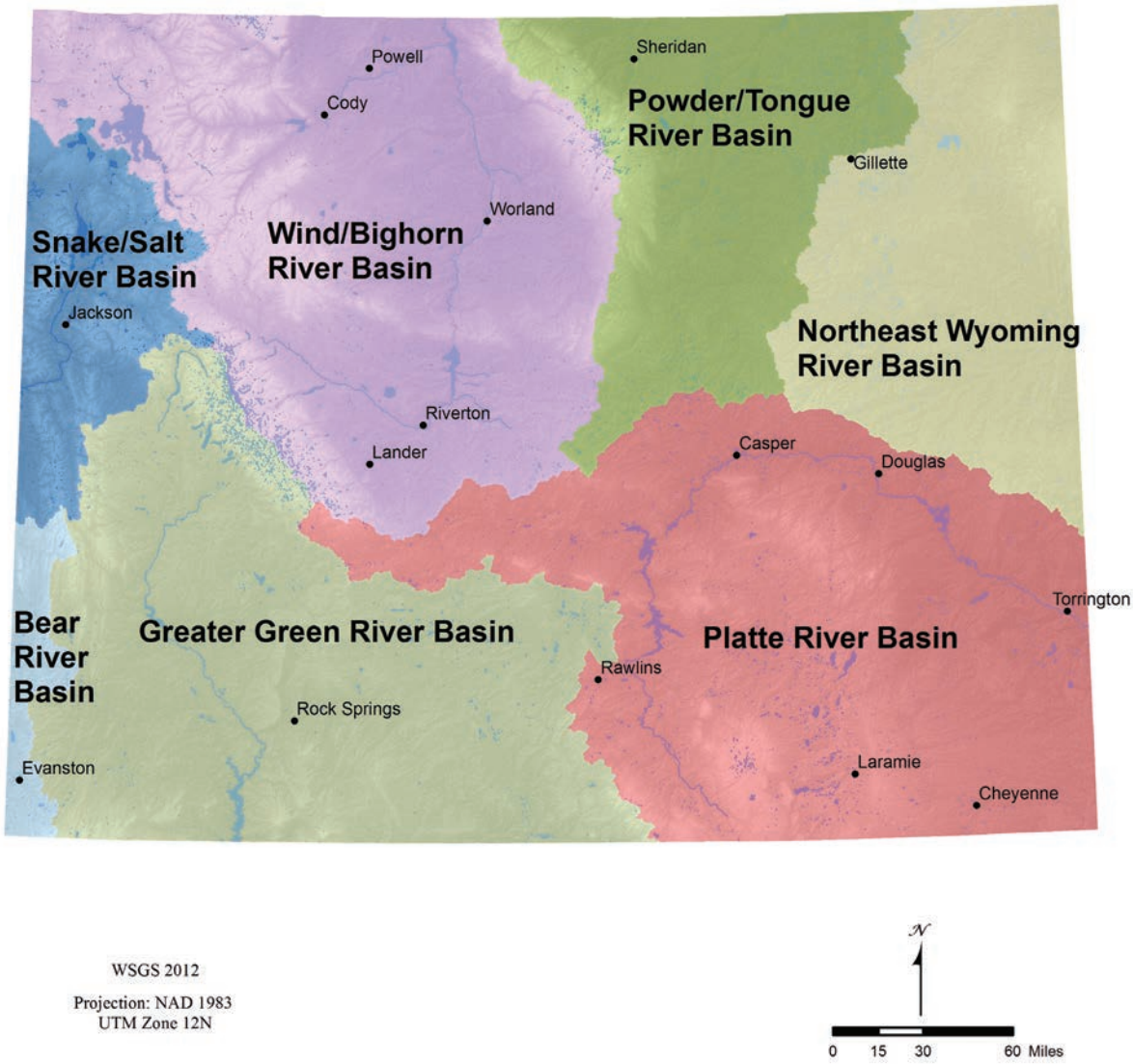

Figure 1-1. Major drainage basins, Wyoming.

described in **Appendix A** were organized into comprehensive hydrostratigraphic charts and a surface hydrogeology map for the Platte River Basin **(Plate 2)**. In some cases, two or more minor aquifers that are hydrologically connected have been grouped together and treated as a single combined hydrogeologic unit. The physical geology of the major landforms within the Platte River Basin is discussed in **Chapter 4.** The geology and hydrogeology of individual Platte River Basin geologic units are discussed in detail in **Chapter** 7.

- **Define the three-dimensional extent of the aquifers.**
  Plate 2 is a map of the outcrop areas for the basin's aquifers and confining units in the Platte River Basin. Nineteen cross sections **(Figures. 9-2– 9-20)** illustrate the subsurface configuration of the geologic units that constitute the hydrogeologic units at selected areas within the Platte River Basin. Isopach maps with substantial coverage of the major aquifers in the Platte River Basin are not available.
  - **Describe the following hydraulic, hydrogeologic and hydrogeochemi-**

cal properties of the aquifers and confining units:

- Physical characteristics - **Chapter 7** describes the lithologic and hydrogeologic characteristics of the hydrogeologic units identified in **Plate 2**.
- Water chemistry with comparisons to applicable state and federal regulatory standards by class of use – **Chapters 5** and **7** contain extensive discussions of basin water quality with comparisons to regulatory standards, statistical analyses of water chemistry are presented in **Appendices E1 - F6** and **Chapter 5** and trilinear diagrams are provided in **Appendices G1 – H4**.
- Principal potential pollutants - **Section 5.7** contains a discussion of potential sources of pollution and maps of these facilities are provided in **Figures 5-4** through **5-10,**

- **Estimate the quantity of water in the aquifers.**
  Data sufficient for a basin-wide aquifer-specific assessment of groundwater quantity is not available and is unlikely to ever be developed. The complex geology of most of the Platte River Basin does not lend itself to the general assumptions about aquifer properties, geometry, and saturated thickness that would be required for a plausible estimate of total and producible groundwater resources. Important aquifers in the Platte River Basin, such as the High Plains, Casper, and Split Rock aquifers, have been described in numerous specific studies that are more comprehensive and relevant than a summary estimate. Groundwater resource estimates are addressed in this Technical Memorandum by analysis of recharge **(Chapter 6)** and a basin-wide water balance **(Chapter 8)**.
- **Describe the aquifer recharge areas.**
  Plate 2 is a map of the outcrop areas of aquifers and confining units in the Platte River Basin. Maps that depict the outcrop areas used to calculate the annual rate of recharge for specific aquifers and logical groups of aquifers throughout the Platte River Basin are provided in **Figures. 6-1 – 6-6**. Recharge is discussed in **Section 5.1** and **Chapter 6**.
- **Estimate aquifer recharge rates.**
  Existing maps depicting average annual precipitation **(Figure 3-3)** and estimated recharge rates **(Figure 5-2)** over the entire Platte River Basin were adapted for presentation in this Technical Memorandum. Existing annual recharge rates were multiplied by aquifer outcrop areas **(Figures 6-1 – 6-6)** to estimate a range of annual recharge volumes for individual and combined aquifers. The results of these estimates are summarized in **Tables 6-1** through **6-3** and discussed in **Section 6-2. Figure 6-7** represents recharge as a percentage of precipitation and **Section 6-2** describes how recharge efficiency varies by individual and combined aquifers overall within the Platte River Basin.
- **Estimate the "safe yield" potential for the aquifers and describe implications of hydrologically connected groundwater and surface water.**
  The difficult and controversial concept of "safe yield" has been discussed at length by many authors. Originally, the concept was defined as the volume of water that could be pumped, "regularly and permanently without dangerous depletion of the storage reserve" (Lee, 1915). Meinzer (1923) defined safe yield as, "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." By these definitions, safe yield

is determined solely on the basis of storage depletion and does not directly consider recharge or natural discharges to springs, to surface water bodies and to deep basins. Ideally, however, new groundwater development projects would not decrease surface water flows but would capture water that would otherwise flow deeper into a basin where production is precluded by economic or water quality limitations. Lacking accurate data for either recharge or total discharge (which are rarely known), it is difficult to derive a meaningful value for safe yield. Adequate data does not exist and will probably never be developed for an accurate basin-wide aquifer-specific estimate of safe yield in the Platte River Basin; however, total (average annual) recharge for the various aquifers and groups of aquifers is estimated in **Chapter 6**, and these estimates can be used as upper limits of safe yield for the Platte River Basin aquifers. In some cases, rational estimates of safe yield can be calculated for specific well-delineated prospects. Safe yield is further discussed in **Section 5.1.4**. Areas where groundwater uses may impact surface water flows, as defined by the 2001 Modified North Platte Decree, and where development may be restricted by other institutional constraints are shown on **Figure 9-1** and discussed in **chapters 8** and **9** and **Appendix D**.

- **Describe and evaluate existing groundwater studies and models:** Existing groundwater models are identified and evaluated; and recommendations for future groundwater modeling in the Platte River Basin are discussed in **Chapter 7.** Existing groundwater studies are discussed in **Chapter 7** and **Appendix B** and are cited throughout this report.
- **Identify future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands:** Several approaches to address future groundwater development potential are discussed in **Chapter 9**. General and aquifer-specific hydrogeology relative to groundwater development potential is discussed in **Chapters 4, 5, 6, and 7**.
  - **Figures 8-1 through 8-34** show wells permitted in the Platte River Basin sub-regions **(Chapter 2)** by the SEO through February 14, 2011. These figures contain selected groundwater permit statistics and illustrate historic groundwater development patterns relative to sub-region hydrogeologic unit outcrop patterns. SEO permits issued for the period from January 1, 2005 through February 14, 2011, shown on inset tables contained within these figures, illustrate the focus of recent groundwater development efforts. Existing groundwater development in the Platte River Basin is discussed in **Chapters 7, and 8**.
  - A summary of groundwater development studies and projects in the Platte River Basin, sponsored by the WWDC, is included in **Appendix B**. The development potential of specific aquifers based on information compiled from these and other previous studies is described in **Chapter 7** and summarized in **Chapter 9**.
  - Groundwater development prospects for the Platte River Basin, identified in the 2005 Available Groundwater Determination (Lidstone and Associates, Inc., 2005b) and areas where groundwater development may be restricted by groundwater control districts or the Decree are shown in **Figure 9-1** and briefly

discussed in **Chapter 9**.
  - Current WWDC and SEO projects related to groundwater development in the Platte River Basin are discussed in **Chapter 9**.

1.2 Agency participation

This Technical Memorandum is the result of a cooperative effort by the WWDC/WWDO, WSGS, USGS, and the Water Resources Data System (WRDS). The WSEO and the Wyoming Department of Environmental Quality (DEQ) contributed significant resources for developing some of the data presented in this Technical Memorandum.

- The WWDO and WRDS provided the WSGS with overall program guidance and standards, software, and format requirements for deliverables (maps, databases, metadata, tables, graphs, etc.).
- The WSGS was the primary compiler of the information developed in **Chapters 1, 2, 3, 4, 5, 6, 8, and 9**.
- The USGS, under contract with the WSGS, compiled the information used in **Chapter 7**, and associated **Section 5.6.1**.
- The WSGS and USGS cooperated on sections of **Chapter 5**.
- The WRDS provided assistance by providing hard copies of the final Technical Memorandum and will feature the associated deliverables on its website at http://www.wrds.uwyo.edu on behalf of WWDC/WWDO.

The WWDC, the water development planning agency for Wyoming, administers publicly-funded development, construction, rehabilitation, and related groundwater projects through its professional, legal, and support staff at the WWDO.

The WSGS is a separate operating agency under the executive branch of state government (W.S. 9-2-801, 9-2-803 through 9-2-810). The WSGS' purposes are:

- To study, examine, and understand the geology, mineral resources, and physical features of the state;
- To prepare, publish, and distribute (free or for sale) reports and maps of the state's geology, mineral resources, and physical features; and,
- To provide information, advice, and services related to the geology, mineral resources, and physical features of the state.

The agency's mission is to "promote the beneficial and environmentally sound use of Wyoming's vast geologic, mineral, and energy resources while helping protect the public from geologic hazards." By providing accurate information and expanding knowledge through the application of geologic principles, the WSGS contributes to the economic growth of the state and improves the quality of life of Wyoming's residents.

The USGS provides data, maps, reports, and other scientific information to help individuals, local and state governments to manage, develop, and protect America's water, energy, mineral, and land resources. The agency's mission is to "provide reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life." To meet these goals, the USGS employs experienced scientists and support staff from a wide range of earth and life science disciplines.

The WRDS is a clearinghouse for hydrological data. The WRDS is funded by the WWDO to provide a variety of services, including the online provision of groundwater resources information, maps, and publications.

The WSEO and WWDO cooperate on many projects. WSEO personnel attend meetings on river basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the WSEO and WDEQ (K. Clarey, WWDC, personal communication).

1.3 Legal and Institutional Framework

Wyoming laws that govern the appropriation, development, and beneficial use of water resources

are based on the doctrine of prior appropriation, commonly stated as *"first in time is first in right."* This means that the first party to put a source of water to beneficial use has a "priority" water-right that will be honored prior to those of other users with later water-rights during periods of limited supply. A special provision is that municipalities can obtain water-rights from earlier priority uses through eminent domain under specific conditions. Because all waters within Wyoming are property of the state, a water-right does not grant ownership, but only the right to use water for beneficial purposes. Use of water resources for domestic and livestock purposes customarily take precedence over other uses. In Wyoming, water-rights are attached to the land but can be transferred. The laws and regulations pertaining to the appropriation, development, and beneficial use of groundwater are administered by the SEO and Board of Control comprised of the superintendents of the four state water divisions and the State Engineer. The entire Platte River Basin area is included in Water Division 1. Comprehensive discussions of the laws that govern Wyoming water resources are provided online at:

http://seo.state.wy.us/PDF/b849r.pdf and http://seo.state.wy.us/PDF/b-969r.pdf

1.3.1 Wyoming water law – groundwater appropriation, development, and use

Groundwater within the state is owned and controlled by the state of Wyoming. Under Wyoming law, groundwater includes any water (including geothermal waters) under the land surface or under the bed of any body of surface water. The SEO is responsible for the permitting and orderly development of groundwater in Wyoming and for protecting groundwater resources from waste. The updated Wind/Bighorn River Basin Water Plan (MWH, and others, 2010) provides the following discussion of Wyoming water law specific to groundwater:

> "Wyoming's groundwater laws were originally enacted in 1945 and amended in 1947. These laws were replaced by new groundwater laws on March 1, 1958, which were then amended in 1969. Groundwater is administered on a permit basis. The acquisition of groundwater rights generally follows the same permitting procedures as surface water rights, except that a map is not required at the time of permit application. Applications are submitted to and approved by the WSEO prior to drilling a well. With the completion of the well and application of the water to a beneficial use, the appropriation can then be adjudicated. The issuance of well permits carries no guarantee of a continued water level or artesian pressure."

> "As with surface water rights, groundwater rights are administered on a priority basis. For all wells drilled prior to April 1, 1947, a statement of claim process was followed to determine the priority date of the well. For wells drilled between April 1, 1947 and March 1, 1958, the priority date is the date the well was registered. For wells drilled after March 1, 1958, the priority date is the date the application was received at the WSEO."

> "Domestic and stock wells are those wells used for non-commercial household use, including lawn and garden watering that does not exceed one acre in aerial extent, and the watering of stock. The yield from these wells cannot exceed 25 gallons per minute (gpm). ... The Groundwater Division also issues permits for spring developments where the total yield or flow of the spring is 25 gpm or less and where the proposed use is for stock and/or domestic purposes."

1.3.2 Interstate agreements

Flows are generally subject to strict water rights. Surface water resources of Wyoming are subject to interstate agreements that generally limit how much streamflow can be depleted before leaving the state.

Tributary interconnection between groundwater and surface water is a prominent water-rights issue in the Platte River Basin and conflicts among users within the state or across state lines can occur where groundwater extraction affects surface flows. In the Platte River Basin there are significant judicial and regulatory constraints on the development of groundwater pursuant to the "Modified North Platte Decree" and the "Platte River Recovery Implementation Program."

In 2001 the Modified North Platte Decree between the states of Wyoming and Nebraska resolved decades of litigation over the water resources of the North Platte River Basin. In specific areas of the Platte River Basin, the Modified North Platte Decree restricts Wyoming diversions of groundwater with priority dates later than 1945 that are hydrologically connected to surface water. Criteria were developed under the North Platte Decree for identifying areas where groundwater is hydrologically connected. Based on these criteria, the SEO developed "green area" maps for the Modified North Platte Decree Committee; groundwater in the designated areas or which otherwise meets the Decree criteria is considered to be not hydrologically connected to surface water (**Figure 9-1)** for purposes of Decree enforcement. Groundwater prospects identified in previous studies (Lidstone and Associates, 2005b; Trihydro Corporation, 2004 and Trihydro Corporation, 2007a) that focused on developing potentially large-volume non-connected groundwater sources to augment surface flows are shown on the map inset on **Plate 2**.

In 1997, the states of Wyoming, Colorado, and Nebraska, and the U.S. Department of the Interior developed the Platte River Recovery Implementation Program (PRRIP) to address several issues under the Endangered Species Act (ESA) related to the current use and future development of Platte River Basin water resources. The PRRIP has two primary objectives:

1. To maintain, improve, and conserve water-dependent habitat on behalf of four threatened and endangered species, with populations located along the Platte River in central Nebraska.
2. To allow current use and future development of water resources in the Platte River Basin to proceed without additional ESA requirements related to these threatened and endangered species.

Because the depletion of surface water resources through the use of hydrologically connected groundwater would impact habitats of concern, the parties to the PRRIP adopted the hydrological connection criteria from the North Platte Decree.

Appendix D (Hinckley, 2011) describes the background and history of the Decree and the PRRIP, and the criteria used for determining whether groundwater is hydrologically connected to surface water under these programs. Groundwater prospects located outside of the designated areas (in areas where groundwater and surface water "have not been" determined to be not hydrologically interconnected) may be developed depending on the results of site-specific hydrogeologic investigations performed consistent with the criteria outlined in the Modified North Platte Decree.

Furthermore, there are additional criteria used by the SEO to assess the depletive quantity of groundwater wells that are hydrologically connected to the surface water flows in the North Platte River Basin. If projected depletions from these wells are less than benchmarks specified by the SEO, the wells are approved to permit status if the State of Wyoming agrees to cover the depletions as described in the Wyoming Depletion's Plan.

1.3.3 Wyoming water law – groundwater quality

The Denver office of the U.S. Environmental Protection Agency (EPA) Region 8 has primary control (primacy) over Wyoming's public drinking water supplies. Wyoming is the only state in which EPA has primacy over drinking water systems. The EPA monitors water quality for the several hundred public water systems in Wyoming. Information on Wyoming's public drinking water systems is available on the EPA Wyoming Drinking Water website:

http://www.epa.gov/safewater/dwinfo/wy.htm

Except on the Wind River Indian Reservation, the DEQ enforces groundwater quality regulations under the Wyoming Environmental Quality Act, with guidance from the Wyoming Environmental Quality Council. The DEQ administers provisions of the Federal Clean Water Act Amendment of 1972 (Section 208) that provide for water quality management by state and local governments, as well as provisions of the Federal Water Pollution Act, by developing a State Water Quality Plan approved by the EPA. In general, operations under the jurisdiction of the Wyoming Oil and Gas Conservation Commission (WOGCC), U.S. Bureau of Land Management (BLM), EPA, or U.S. Forest Service that cause groundwater contamination are referred to the DEQ; The WOGCC has jurisdiction over Class II underground injection wells dedicated to disposal of produced water from state and federal oil and gas leases, respectively.

1.3.4 Other agencies

The U.S. Bureau of Reclamation (BOR), an agency under the U.S. Department of the Interior, oversees and manages water resources specifically related to the operation of numerous water diversion, delivery, storage, and hydroelectric power generation projects built by the federal government throughout the western United States. The BOR cooperates with the SEO and the WWDC (primarily through the SEO), but as a federal agency has autonomy to execute some programs unilaterally. The BOR coordinates releases from Wyoming's reservoirs with the SEO. (K. Clary, WWDC, personal communication). Although not a primary area of concern, the BOR and the following other agencies are occasionally involved in groundwater resource issues:

- Wyoming Department of Agriculture
- U.S. Department of Agriculture
- U.S. National Park Service
- U.S Army Corps of Engineers
- U.S National Resources Conservation Service
- USDA Soil Conservation Service
- U.S. Office of Surface Mining, Reclamation and Enforcement
- U.S Bureau of Ocean Energy Management and the Bureau of Safety and Environmental Enforcement
- U.S Department of Energy
- U.S. Nuclear Regulatory Commission

1.3.5 Authorship

The principal authors of this Technical Memorandum are:

Paul Taucher, WSGS and Energy Compliance LLC, Laramie, Wyoming

Timothy T. Bartos, USGS, Wyoming Water Science Center (WWSC), Cheyenne, Wyoming

Karl Taboga, WSGS, Laramie, Wyoming

Additional authors and coauthors of specific sections of this Technical Memorandum are:

Chapter 5: Keith Clarey, WWDC, Cheyenne, Wyoming; Laura L. Hallberg, and Melanie L. Clark, USGS, WWSC, Cheyenne, Wyoming; James Stafford, WSGS.

Chapter 7: Laura L. Hallberg, and Melanie L. Clark, USGS, WWSC, Cheyenne, Wyoming

Appendix A: Brett Worman, Dave Copeland, and Scott Quillinan, WSGS, Laramie, Wyoming

Appendix B: Brett Worman and Richard Hays, WSGS, Laramie, Wyoming

Appendix C: Tomas Gracias, WSGS, Laramie, Wyoming

Appendix D: Bern Hinckley, WSGS and Hinckley Consulting, Laramie, Wyoming

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The authors wish to thank all these named and many unnamed who helped during the preparation of this report.

Chapter 2

Background

Paul Taucher and Karl Taboga

A wide variety of available information was reviewed and compiled for this updated and expanded study of Platte River Basin groundwater resources. The updated data was obtained from regional and area-specific studies conducted by state and federal agencies in Wyoming, Colorado, and Nebraska. This chapter discusses the data sources, approach, organization and computer-based mapping used in this current study and compares them to the previous Available Groundwater Determination (Lidstone and Associates, 2005b), and other studies.

The 2006 Platte River Basin Plan (Trihydro Corporation and others, 2006a) and associated Technical Memoranda constitute the most recent of the studies completed by the Wyoming Water Development Commission (WWDC) between 2000 and 2006 for Wyoming's seven major drainage basins. The 2006 plan provides extensive information about the cultural and physical settings of the basin both generally and as they relate to groundwater resources. In order to avoid repetition, the 2006 plan and 2007 Wyoming Framework Water Plan that summarizes and updates the 2006 Platte River Basin plan – (WWC Engineering, Inc. and others, 2007) are cited frequently in this study, and links are provided to online information where appropriate.

2.1 Sources of data

Agencies that contributed data and information for this study include:

BLM	U.S. Bureau of Land Management
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UW	University of Wyoming Libraries
WRDS	University of Wyoming Water Resources Data System
DEQ	Wyoming Department of Environmental Quality
WyGISC	Wyoming Geographical Information Science Center
WOGCC	Wyoming Oil and Gas Conservation Commission
WRRI	Wyoming Water Resources Research Institute
SEO	Wyoming State Engineer's Office
WSGS	Wyoming State Geological Survey
WWDC	Wyoming Water Development Commission
WWDO	Wyoming Water Development Office

2.2 Previous regional-scale investigations

Several surface water and groundwater resource management studies have been previously conducted for areas contained wholly or partly within the Platte River Basin. The geographic scale of the earlier projects varies considerably. Most of the previous investigations examined the water resources of structural basins located in one or more Wyoming counties; however, other studies concentrated on areas defined by small watersheds up to multi-state regions. This study builds on those previous compilations. The primary regional-scale hydrogeologic studies of the basin area are listed below in approximate chronologic order by agency and author(s):

- *U.S. Geological Survey Hydrologic Investigation Atlases*
  - 1966 - Welder, G.E., and McGreevy, L.J., 1966, Ground-water reconnaissance of the Great Divide and Washakie basins and some adjacent areas, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas 21 HA-219, 3 sheets, 10 p.
  - 1968 - Whitcomb, H.A., and Lowry, M.E., 1968, Ground-water resources and geology of the Wind River Basin area, central Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-270, 3 sheets, 13 p.
  - 1973 - Hodson, W.G., Pearl, R.H., and

Druse, S.A., 1973, Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-465, 4 sheets.

1973 - Lowry, M.E., and Rucker, S.J., IV, Wahl, K.L., 1973, Water resources of the Laramie, Shirley, Hanna, and adjacent areas, southeastern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-471, 4 sheets.

1996 - Whitehead, R.H., 1996 Ground water atlas of the United States, Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geologic Survey Hydrologic Investigations Atlas HA-730-I, 24 p.

- *Basin studies by the University of Wyoming, Water Resources Research Institute and the Wyoming Natural Resource Board*

1962 - Dana G. F., 1962, Ground water reconnaissance study of the State of Wyoming, Introduction and seven basin reports, 1. Denver-Julesburg basin, 2. Laramie-Hanna-Shirley basins, 3. Washakie-Red Desert basins: prepared for Wyoming Natural Resource Board, Cheyenne, 355 p.

1980 - Feathers, K.R., Libra, R., and Stephenson, T.R., 1980, Occurrence and characteristics of ground water in the Powder River Basin, Wyoming: Laramie, WY, University of Wyoming, v. I-A.

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2.3 Current USGS regional-scale investigations

In addition to the existing regional-scale studies listed above, the U.S. Geological Survey (USGS) is currently conducting an extensive hydrogeologic investigation of the High Plains, Lance and Fox Hills aquifers in the Denver Basin near the Town of Pine Bluffs.

2.4 Current Available Groundwater Determination

The boundaries of the previous regional hydrogeologic investigations of the Platte River Basin were generally based on structural basins, counties, or other specific areas of interest. The study area of this and the previous memoranda (Lidstone and Associates, 2005b) include the surface drainages of the North and South Platte rivers that lie within the borders of the state of Wyoming as well as small watersheds in Colorado and Nebraska that are tributary to the Wyoming Platte River Basin **(Figure 3-2)**. Due to the complexity of the Platte River Basin's geologic and hydrologic settings and its sheer size, this study examines the basin's groundwater resources in logically established sub-areas; by drainage sub-basins in the 2005 Groundwater Determination and by sub-regions delineated based on geologic and hydrogeologic criteria in this study.

The previous Platte River Basin Final Report (Trihydro Corporation and others, 2006a) partitioned the Platte River Basin into the following seven ***surface-drainage sub-basins*** for discussing both surface water and groundwater:

- Above Pathfinder Dam
- Pathfinder to Guernsey
- Guernsey to State Line
- Upper Laramie
- Lower Laramie
- Horse Creek
- South Platte

These sub-basins were defined by Wyoming Level 6 Hydrologic Unit Boundaries (scale 1:24,000) developed by the USGS and the University of Wyoming using USGS hydrologic unit codes (HUCs). The Wyoming Level 6 Hydrologic Unit Boundaries were matched, with modification to the seven Platte River Basin sub-basin boundaries described in the 2001 Nebraska v. Wyoming Final Settlement Stipulation and Modified Decree. A more comprehensive discussion of how the sub-basins were established for the 2006 Platte River Basin Final Report is provided by Trihydro Corporation (2005f).

To facilitate the cartographic presentation of high resolution water resource information contained within some sections of this Memorandum, WSGS divided the Platte River Basin into ***seven geologic sub-regions*** **(Figure 3-1)** that exhibit distinct geologic, hydrogeologic, and geographic characteristics. This approach is used, most notably, in the summary geology and hydrogeology section of **Chapter 4** and the groundwater permit/well data from the WSEO database **(Chapter 8)** of this study. The sub-regions based on the stratigraphic regions and associated correlation diagrams of Love and others (1993) include:

- Casper Arch
- Denver Basin
- Granite Mountains
- Great Divide Basin
- Hanna Basin
- Hartville Uplift
- Laramie Basin
- Laramie Mountains
- Medicine Bow Mountains
- Powder River Basin
- Rawlins Uplift
- Saratoga Valley
- Sierra Madre Mountains
- Shirley Basin
- Wind River basin

Figure 7-1 was also compiled by WSGS to support the presentation of the aquifer-specific data

compiled by USGS for **Chapter 7** of this study. The sub-regions defined on both **Figures 3-1 and 7-1** are based on the stratigraphic regions (and associated correlation diagrams) established by Love and others (1993). **Figures 3-1 and 7-1** divide the Platte River Basin study area into seven sub-regions. Although both figures were developed with respect to the same stratigraphic regions, because they were developed for different purposes, the sub-regions differ somewhat between the two maps, both in their boundaries and how they are named and referenced in this study. The following table compares the similar sub-regions established in **Figures 3-1 and 7-1**.

- **Plate S.** Relation of lithostratigraphic units to hydrogeologic units, Rawlins uplift.
- **Plate T.** Relation of lithostratigraphic units to hydrogeologic units, Sierra Madre, Medicine Bow Mountains, and Saratoga valley.
- **Plate U.** Relation of lithostratigraphic units to hydrogeologic units, Hanna and Laramie basins.
- **Figure 7-2.** Relation of Cenozoic lithostratigraphic units to hydrogeologic units, High Plains aquifer system, southeastern Wyoming.

Table 2-1 – Platte River Basin sub-regions for data presentation

Figure 3-1 sub-regions	**Figure 7-1** sub-regions
Casper Arch and Powder River and Wind River Basins	Central Wyoming Basins North
Denver Basin and Hartville Uplift	Great Plains
Granite Mountains and Shirley Basin	Sweetwater Arch
Laramie and Hanna Basins	Central Wyoming Basins South
Laramie Mountains and Central Uplifts	Laramie Mountains
Sierra Madre and Medicine Bow Mountains	Sierra Madre / Medicine Bow Mountains
Wind River Mountains and Great Divide Basin	Central Wyoming Basins South

Detailed hydrostratigraphy of the Platte River Basin was developed by the USGS for this study. Because of the geologic and hydrologic complexity of the basin, the updated hydrostratigraphy was also established for sub-regions based on stratigraphic regions by Love and others, (1993). Development of the updated hydrostratigraphy is described in **Chapter 7** and summarized on hydrostratigraphic nomenclature charts **(Plates J, K, M, S, T, U** and **Figure 7-2)**, and on **Plate 2.**

Although a map delineating the hydrostratigraphic sub-regions was not developed, the following plate/figure titles describe the general areas where they apply:

- **Plate J.** Relation of lithostratigraphic units to hydrogeologic units, Granite Mountains uplift and Shirley Basin.
- **Plate K.** Relation of lithostratigraphic units to hydrogeologic units, Hartville uplift and Laramie Mountains.
- **Plate M.** Relation of lithostratigraphic units to hydrogeologic units, Denver-Julesberg Basin.

This updated Available Groundwater Determination provides expanded information on several topics, developed to more fully characterize the groundwater resources of the Platte River Basin:

- Effects of structure **(Section 5.4 and Chapter 7)** on groundwater distribution and flow;
- Discussion of deep basin hydrogeology **(Section 5.5)**;
- Potential hydrothermal resources **(Chapter 4)**;
- Aquifer vulnerability and potential sources of groundwater contamination **(Section 5.7)**;
- Comparisons of calculated aquifer(s)-specific recharge volumes with updated precipitation data, and current and projected beneficial uses (**Section 6.2**);
- A basin-wide water balance **(Chapter 8)**;
- A detailed listing and summary of historic groundwater development studies by the WWDC in the Platte River Basin **(Appendix B)**.

2.5 Maps

Progressive improvements in geographic information system (GIS) technology have greatly enhanced the geologist's ability to process and present large, complex geospatially linked datasets for natural resource evaluations. To meet the objectives of this updated Available Groundwater Determination, the WSGS and USGS developed a series of maps to present and evaluate the extensive digital data resources available on Platte River Basin groundwater resources. Several maps were generated wholly or primarily from existing GIS databases compiled specifically for this study. Some of the maps and layers were supplemented with information scanned or digitized from existing hard copy maps into GIS-supported formats.

The accuracy of any map or figure depends on the accuracy of the original data and the methods used to process it. Frequently, data processing for large compilations requires that correlations be made between multiple, disparate data sets. The limitations of the data used in digital mapping make it necessary for the analyst to provide the reader with interpretive qualifications regarding the reliability of the produced maps and figures. This memorandum provides discussions of data limitations and development processes and cites data sources for each map and figure presented.

Additionally, *metadata* (qualifying information on the GIS datasets) is furnished along with the GIS data. Metadata provides structured and detailed descriptive information about the data resources used to develop GIS map layers. Metadata facilitates the understanding, use, and management of the data by defining its sources, locations, formats, attributes, processing, limitations, disclaimers, etc. Where appropriate, the metadata includes contact information where additional information can be obtained. The metadata associated with the Platte River Basin maps are provided on-line at http://waterplan.state.wy.us/plan.

WSGS and USGS generated the maps for this study in two formats. Plate-scale maps use 1:380,000 scale (1 inch = 6 miles). Figure-scale maps use variable scales that allow the maps to fit either 8½ × 11-inch, or 11 × 17-inch sheets depending on the amount of data presented and readability considerations.

Chapter 3

Description of the study area

Paul Taucher, James Stafford and Karl Taboga

The Platte River Basin drainage basin covers approximately one quarter of the state in southeastern and central Wyoming, plus smaller areas of northern Colorado and western Nebraska. The basin comprises approximately 24,106 square miles (15.43 million acres) in Wyoming, 2,074 square miles (1.33 million acres) in Colorado, and 109 square miles (0.07 million acres) in Nebraska. In Wyoming, the Platte River Basin includes all of Albany, Laramie, and Platte counties, parts of Goshen (95.9%), Carbon (70.8%), Natrona (57.2%), Converse (49.9%), and Fremont (18.9%) counties, and small undeveloped parts of southwestern Niobrara, western Sublette, and northern Sweetwater counties. In Colorado, the basin covers all of Jackson County, 16.5 percent of Larimer County and a small area of northern Weld County, and small areas of Scottsbluff and Sioux counties in Nebraska. **Figure 3-1** shows the boundary of the Platte River Basin in relation to state and county borderlines for all three states.

Although, the Platte River Basin encompasses about 25 percent of Wyoming's total surface, it serves as home to approximately 231,000 people or about 41 percent of the state's current population (2010 census). The basin contains the state's three largest incorporated municipalities (Cheyenne, Casper, and Laramie) and several larger towns such as Rawlins, Douglas, and Wheatland as well as numerous smaller towns and a substantial rural population. **Figure 3-1** is an index map that shows townships, major, roads and incorporated municipalities within the overall Platte River Basin, and the hydrogeologic sub-regions that were established for this study within the Wyoming area of the basin **(Chapter 2)**.

3.1 Physiography, landforms, topography, and surface drainage

The greater Platte River drainage basin is located within areas of the southern Rocky Mountain, Wyoming Basin, and Great Plains Physiographic provinces. The uplifts and basins that constitute the Platte River Basin were introduced in **Chapter 2.** Major drainages, reservoirs, and physiographic features of the Platte River Basin are shown on **Figure 3-2**. A map of the physiographic provinces of Wyoming can be found on the WSGS website at http://www.wsgs.uwyo.edu/Research/Geology/images/Final/Elevations.pdf, and a map of the South Platte River drainage basin can be found at http://co.water.usgs.gov/nawqa/splt. The southern Rocky Mountain Province contains the Laramie, Medicine Bow, and Sierra Madre mountain ranges; areas east and northeast of the Laramie Mountains and Casper arch are within the Great Plains Province; and the remainder of the Platte River Basin to the west and northwest of the southern Rocky Mountain Province is within the Wyoming Basin Province.

The overall physiography of the Platte River Basin reflects a deeply eroded geologic foundation of large anticlinal uplifts that have crystalline basement complexes exposed in their cores bordering large-scale synclinal basins filled with varying thicknesses of sedimentary rocks. Concurrent uplift and erosion of the highlands, and downwarping and deposition in the basins during the Laramide orogeny was followed by continued uplift, faulting, erosion, mass wasting, and fluvial processes. This resulted in the current physiography characterized by mountains of variable areal scale and elevation, valleys, rolling plains, plateaus, escarpments, bluffs, hills, drainage ways, and small local basins. Elevations in the Platte River Basin range from 4,025 feet above mean sea level at the North Platte River where it crosses the Wyoming-Nebraska state line, to 12,013 feet at Medicine Bow Peak (Trihydro Corporation and others, 2006a). Detailed discussions of the geography of the seven drainage sub-basins of the Platte River Basin are provided in the 2005 Available Groundwater Determination (Lidstone and Associates, 2005b) and can be accessed online at http://waterplan.state.wy.us/plan/platte/techmemos/TechMemo_3-3_FINAL_lowres.pdf.

Surface drainage in the Platte River Basin is controlled by topography and is essentially equivalent to physiography. Perennial streams receive a large percentage of their source waters from overland flow associated with snowmelt and rainfall that originate in semi-humid and humid mountainous headwater regions and persistent baseflow (Trihydro Corporation and others, 2006a). Most ephemeral flow occurs in response to springtime snowmelt and to intense, short duration

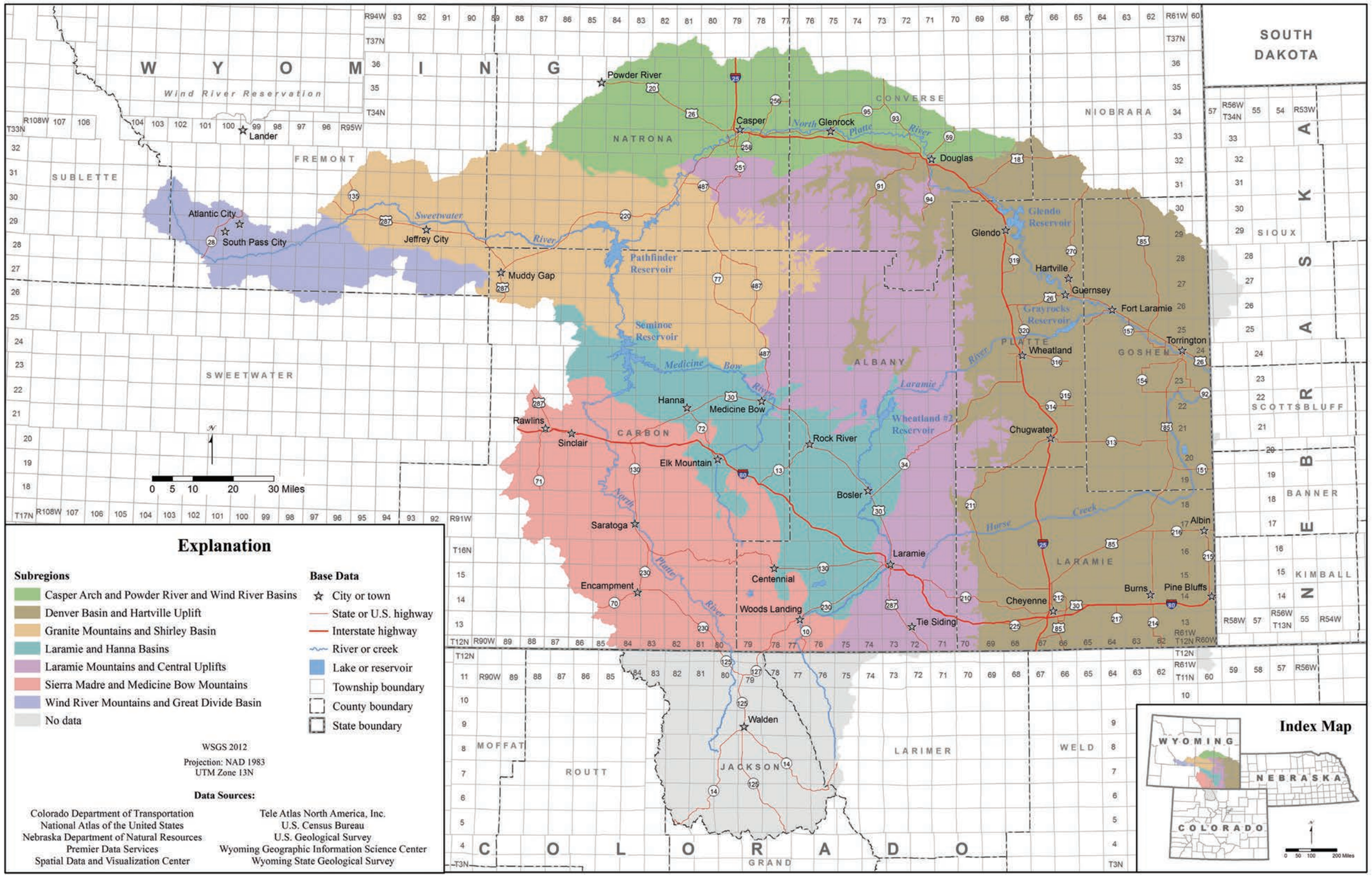


Figure 3-1. Subregion, township, and range index map, Platte River Basin.

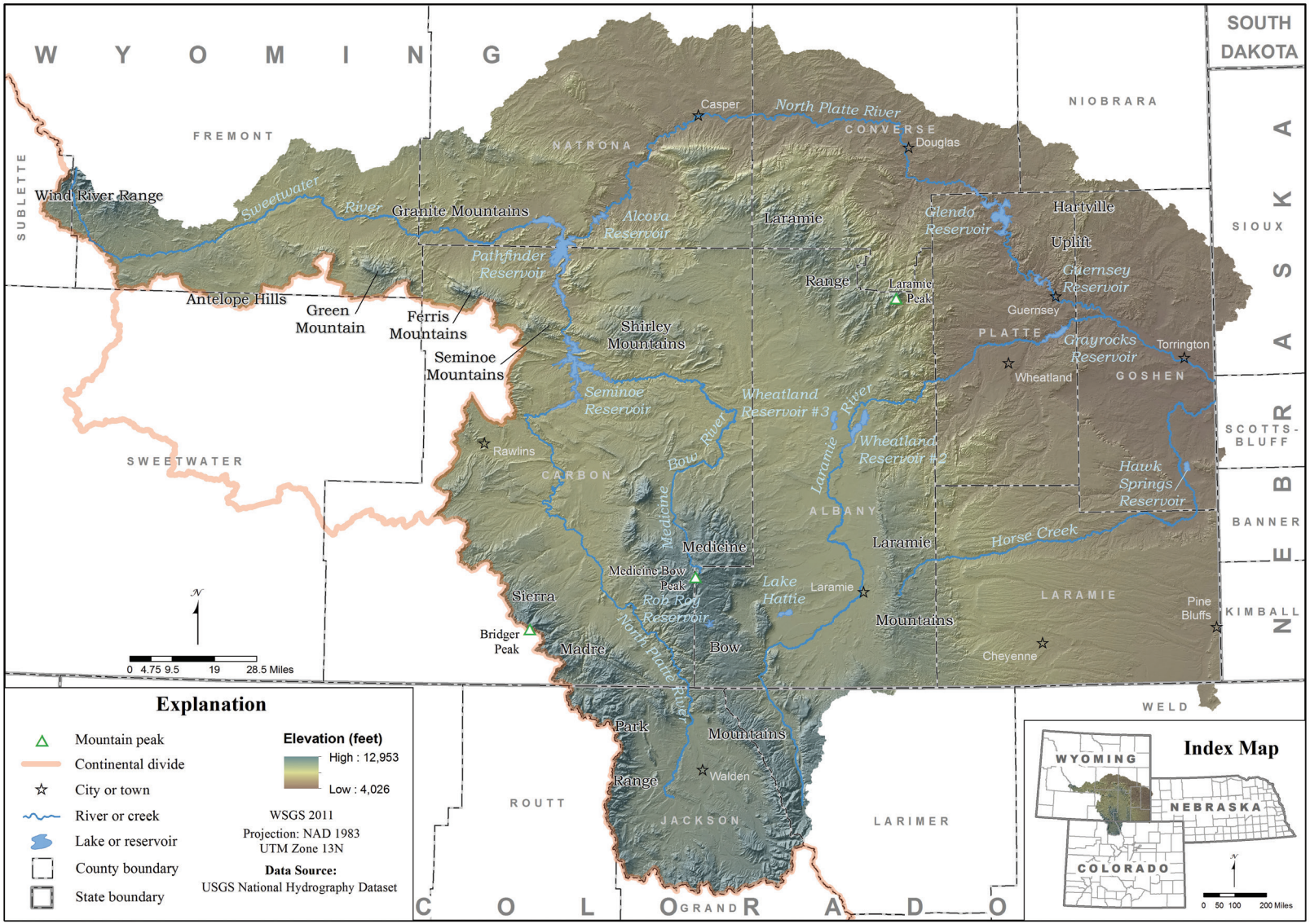


Figure 3-2. Major structural and physiographic features, drainages, and bodies of water, Platte River Basin.

rainfall events characteristic of transient convective thunderstorms. Streamflows are also affected by vegetation, temperature, manmade diversions, and complex interconnections with groundwater. Precipitation and natural streamflow vary by elevation. Annual precipitation increases with surface elevation and can exceed 60 inches a year in the high mountain headwater areas of the Platte River Basin. Most of the basin receives from 9 to 20 inches of precipitation annually (**Figure 3-3**).

Major drainages, reservoirs, and physiographic features of the Platte River Basin are shown on **Figure 3-2**. The basin encompasses the North Platte River and its headwater drainage system, and the northern part of the headwater drainage of the South Platte River (however, the South Platte River does not flow through Wyoming). The Platte River is the major tributary to the Missouri-Mississippi River Basin. Primary tributaries to the North Platte River include the Laramie, Medicine Bow, and Sweetwater rivers. Crow Creek and Lodgepole Creek are Wyoming headwater tributaries to the South Platte River. The distal divides of these drainages define the limits of the Platte River Basin study area. Maps of the surface drainages within the seven drainage sub-basins described in the previous Platte River Basin Water Plan (Trihydro Corporation and others, 2006a) are provided in the Platte River Basin Water Plan, Section 3.2 – Water Atlas (Trihydro Corporation, 2005i) online at http://waterplan.state.wy.us/plan/platte/atlas/index.htm. A map of the South Platte River drainage basin is available at http://co.water.usgs.gov/nawqa/splt.

3.2 Climate, precipitation, and vegetation

Climate within the Platte River Basin is primarily a function of altitude and, to a lesser degree, latitude and topography. Climate types range from semi-arid continental within the basin interiors to humid-alpine in the bordering mountain ranges. The mountain ranges capture much of the atmospheric moisture through orographic uplift that results in increased annual precipitation in the mountainous regions while substantially decreasing precipitation in the basin interiors. Temperature varies by season from well below 0° F in the winter to more than 100° F in the summer. Most precipitation within the basin occurs as snowfall during the winter and early spring and as convective thunderstorms during late spring and summer months (Libra and others, 1981). Average annual precipitation ranges from 9 to 15 inches in the interior basin areas and plains east of the Laramie Mountains; 16 to 30 inches along the foothills adjacent to the mountains, over the lower uplifts, and the high plains around Horse Creek; and 31 to 60 inches in the higher mountain ranges **(Figure 3-3)**.

The distribution of the diverse vegetation within the Platte River Basin is strongly influenced by elevation, soil type, exposure, and precipitation. Approximately half of the basin is rangeland (Kuhn and others, 1983) where the dominant vegetation consists of mixed prairie grasses and shrubs (primarily sagebrush). Cottonwood and Russian olive trees are found along rangeland drainages where elevated soil moisture levels are maintained by perennial or frequent ephemeral streamflows. Fertile bottomlands along the perennial streams have been converted to irrigated cropland. Major crop producing areas are located east of the Laramie Mountains, in the Saratoga valley, west of Laramie, and in the Kendrick Irrigation Project west of Casper. The abundance of grasses, shrubs, and a variety of woodland trees (primarily conifers) and other species generally increases with altitude and increased annual precipitation up to timberline above which vegetation is alpine tundra species of lichens, low shrubs, and grasses. A map illustrating the distribution of the broad categories of vegetation types in the Platte River Basin is provided online in the Platte River Basin Water Atlas (Trihydro Corporation, 2005i) at http://waterplan.state.wy.us/plan/platte/atlas/overview/_general/veg.pdf.

3.3 Population distribution, land use, and land ownership

U.S. Census Bureau data does not provide high resolution population numbers by river basin. A highly accurate population count would prove even more difficult in the Platte River Basin as delineated for this study. Reasonable estimates can be made; however, by processing the most recent census data (U.S. Census Bureau, 2010

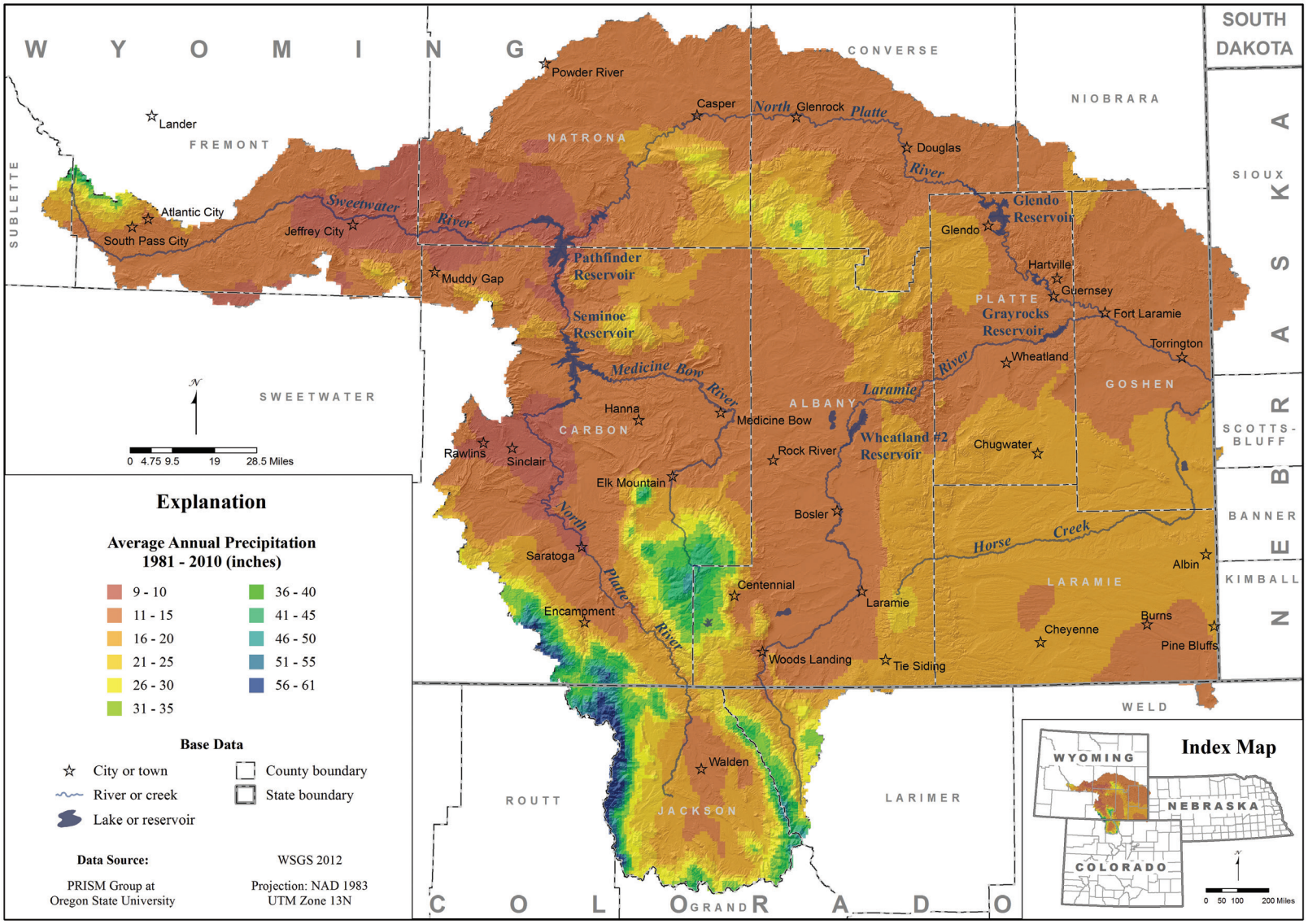


Figure 3-3. Average Annual Precipitation (1981 - 2010), Platte River Basin.

at www.census.gov) for Wyoming counties and municipalities. Using this approach, it is estimated that the 2010 population of the Platte River Basin was approximately 231,000 with about 76 percent residing in cities and towns, and rural populations accounting for the remainder. Except for Cheyenne and Rawlins, which were settled as railroad towns, every large community within the Platte River Basin is located along or within a few miles of a major stream or river. While the planning area encompasses approximately one quarter of the land in Wyoming, in 2010 it contained 41 percent of the state's population and much of its agricultural production (Trihydro Corporation and others, 2006a). Additional detailed information on the demographic conditions of the basin can be found online in the previous 2006 Platte River Basin Final Report at http://waterplan.state.wy.us/plan/platte /finalrept/Final_report.pdf.

Land use in the Platte River Basin is controlled primarily by elevation, climate, the distribution of surface waters, precipitation, the location of mineral resources, and the railroad (in a historical sense). In the high mountain areas above timberline, the alpine lands are generally used only for recreational purposes. At lower elevations, thickly forested areas are utilized for recreation and limited (mostly historic) logging. Grazing is the dominant use on rangelands, foothills, and riparian areas. Agriculture plays a significant role in the basin; approximately 4.1 percent (632,630 acres) of its surface area consists of irrigated cropland (WWC Engineering, Inc. and others, 2007).

Irrigated croplands are located primarily along the rivers and major streams where irrigation with surface water is possible. Most of the basin lowlands are covered sparsely with grasses, sagebrush, and other shrubs and are used for grazing. The locations of active and historic mineral development properties are described in **Section 5.7.2** and shown in figures contained in that section.

Approximately 29 percent of the land area of the Platte River Basin is federally owned. In general, federal land is controlled by the U.S. Bureau of Land Management within the basin lowlands and by the U.S. Forest Service in the forested/mountainous areas. Privately owned lands, concentrated along rivers and streams, constitute about 61.4 percent of the land in the basin; 8.7 percent is owned by the state of Wyoming; and less than 1 percent is owned by other entities. A map of state, federal, and private land ownership in Wyoming is available online at the Wyoming Water Development Office, 2007 Statewide Water Plan Online Presentation Tool: http://waterplan.wrds.uwyo.edu/fwp/figures/pdf/Fig3-2_3-3.pdf (Wyoming Water Development Office, 2007).

Chapter 4

Geologic Setting

Alan Ver Ploeg, Karl Taboga and Paul Taucher

The Platte River Basin drainage basin comprises approximately 24,106 square miles (15.43 million acres) in Wyoming, effectively covering the southeast corner of the state. The geologic setting for the basin is, therefore, both extensive and complex in that it encompasses 4 major Laramide structural basins, overlies small parts of five other Laramide basins and includes five mountain ranges of the southern Rocky Mountains as well as several smaller uplifts. So, a complete description of the geologic framework of the Platte River Basin must include summary accounts of the assemblages of geologic and hydrogeologic units and structural elements that define each of these major structures. To accomplish this, an extensive set of figures and maps, presented as plates, have been prepared for inclusion in this report:

- **Plate 1** illustrates the bedrock geology of the Platte River Basin in Wyoming, Colorado and Nebraska overlain on a base map that shows highway, township, state and county data. Inset maps present the elevations of the Precambrian basement and lineaments (linear geologic features). **Appendix A** contains detailed descriptions of the geologic units shown in **Plate 1**.
- **Plate 2** displays an outcrop map of hydrogeologic units in the Platte River Basin developed by correlating the geospatial data of hydrogeologic units with hydrostratigraphic nomenclature charts **(Plates J, K, M, S, T, and U; Figure 7-2).** The general hydrogeology of the Platte River Basin is discussed in **Chapter 7.** Individual Platte River Basin aquifers are discussed in detail in **Chapter 7, also**.
- Nineteen cross sections, contained in this chapter (**Figures 4-2** through **4-20**), show typical subsurface structure in the Platte River Basin. Isopach maps with substantial coverage of the major aquifers in the Platte River Basin are not available.

4.1 General/historical geology

The Platte River Basin contains simple to complex stratigraphic and structural elements. The configuration of these elements and relationships among them influence the availability of groundwater. The geologic history relevant to groundwater resources of the Platte River Basin begins with the nonconformable deposition of transgressive marine sediments onto Precambrian basement rocks during Middle Cambrian time (Libra and others, 1981; Richter, 1981; Snoke, 1993). From that time forward, a general geologic history that describes the development of the stratigraphic and structural elements the Platte River Basin is as follows:

1. Paleozoic strata in the Platte River Basin were deposited in marine and nonmarine transgressive /regressive environments. Marine limestones and dolomites are the dominant lithologies of the Paleozoic sequence, with less extensive sandstones and shales that represent beach and near-shore environments. Deposition in the Paleozoic Era was broken by long periods of erosion, indicated in the geologic record by several regional unconformities.
2. The early Mesozoic Era was a time when shallow seas deposited interbedded layers (in decreasing abundance) of sandstone, siltstone, shale, carbonates, and evaporites. An emergent transition to a terrestrial environment during the Late Triassic and Early Jurassic Epochs resulted in the deposition of marginal marine, eolian, fluvial, and paludal sandstones and shales.
3. During the Early Cretaceous Epoch a thick section of interbedded shale, sandstone, siltstone, and claystone was deposited under terrestrial, shallow marine and deltaic conditions. Late Cretaceous transgressions and regressions resulted in a thick sequence of interbedded sandstone, siltstone, claystone, and shale deposited in marine, marginal marine, coastal plane, and deltaic environments. Crustal deformation associated with the Laramide Orogeny began in the Late Cretaceous; the Lance Formation recorded the final, eastward retreat of the Cretaceous seas followed by the deposition in terrestrial environments that would prevail

throughout the Tertiary Period.

4. Laramide compressional deformation continued through the early Eocene with large-scale reverse and thrust faults forming the basement-cored mountain ranges and uplifts that surrounded and separated the concurrently subsiding structural basins that make up the Platte River Basin. The uplifted areas were the source of several thousand feet of Tertiary sediments composed of Mesozoic, Paleozoic and Precambrian rocks that were eroded from the uplifts and filled the basins to the extent that all but the highest areas of the surrounding uplifts were buried. These strata are composed of conglomerates, sandstones, and claystones deposited primarily in fluvial, alluvial fan, and lacustrine environments.
5. Late Tertiary normal faulting concurrent with modest extension occurred throughout Wyoming. Uplift during the past 5 million years over a broad area that encompasses the Platte River Basin resulted in the erosion and removal of an enormous volume of Tertiary strata, exhuming the Laramide framework and sculpting the present physiography of the Platte River Basin
6. The youngest geologic units in the basin are unconsolidated Pliocene and Quaternary terrace deposits and Quaternary alluvial deposits of various thicknesses. These deposits, some as much as several hundred feet thick, are composed of conglomerate, gravel, sand, and finer-grained clastic material. The age and occurrence of these deposits have been correlated with recent glacial and interglacial periods by Mackin (1937).

4.2 Structural geology

The Laramide age basins, contained either wholly or partly within the Platte River drainage basins, are small (Carbon basin) to large (Denver basin) asymmetric intermontane structural basins formed during the Laramide Orogeny (Late Cretaceous-Eocene) that contain up to 35,000 feet (Richter, 1981) of Cenozoic, Mesozoic, and Paleozoic sediments deposited on Precambrian crystalline basement rocks (Libra et al., 1981; Richter, 1981). The structural basins are bordered by compressional uplifts cored by Precambrian granite and mantled by moderately to steeply dipping sedimentary formations (Libra et al., 1981). Paleozoic and Mesozoic formations exposed along the flanks of the mountain ranges surrounding the Platte River Basin were folded, faulted, and eroded from the highest areas of the uplifts during the Laramide Orogeny; they now dip basinward at angles ranging from approximately 5 degrees to vertical, and some are overturned. Strata of Paleocene through early Eocene age are also deformed around the perimeters of these structural basins but are mostly flat lying in the interior basin areas. Numerous anticlinal structures with associated faults that formed during the Laramide Orogeny crop out along the margins of the structural basins. **Section 5.4** discusses the substantial influence that structures, primarily those located around the basin perimeters, exert on groundwater recharge, flow and storage.

The topography of the Platte River Basin generally reflects the structure and topography of the Precambrian basement surface formed by uplift, folding, faulting, and erosion of the earth's crust under compressional stress during the Sevier and Laramide orogenies. Downwarping of the structural basins and upwarping and faulting of the uplifts were concurrent; and the upper strata within the basin interiors are composed of Tertiary-age sediment that was eroded from the adjacent uplifts. The structure contour map of the Precambrian basement surface in the Platte River Basin shown on the lower inset map on **Plate 1** shows a general northwest-southeast structural trend. The geologic cross sections on **Figures 4-2** through **4-20** show Precambrian basement rocks overlain by varying thicknesses of Paleozoic through Cenozoic formations, all deformed by large-scale folding and faulting.

The major Laramide structural elements of the Platte River Basin **(Figure 4-1)** comprise:

- The folded and faulted Precambrian basement
- The deeply buried downwarped areas of the Denver, Laramie, Hanna-Carbon,

Shirley, Wind River and Powder River basins

- The mountain ranges and uplifts that surround and separate the basins:
    - The Laramie, Medicine Bow and Sierra Madre/Park mountain ranges
    - Green Mountain, Ferris Mountains, Seminole, and Shirley Mountains
    - The Granite Mountains
    - The Casper Arch and Hartville Uplift
    - The Rawlins Uplift
    - The Wind River Range
    - The structural basins
        - Denver Basin
        - Laramie Basin
        - Shirley Basin
        - Hanna-Carbon Basin
        - Saratoga Valley
        - Great Divide Basin
        - Powder River Basin
        - Wind River Basin

There are many subsidiary structures within the Platte River Basin, some of which are or may be important elements of existing or potential sites for local groundwater development, but discussion of these features is beyond the scope of this study.

4.3 Basin stratigraphy

Geologic units within the structural basins of the Platte River drainage basin vary widely in lithology and distribution, and range in age from Precambrian crystalline rocks to recent alluvial and terrace deposits. The structural basins that compose the Platte River Basin contain up to 35,000 feet, of Cenozoic through Paleozoic sedimentary strata. The explanation on **Plate 1**identifies the geologic units present in the basin; the individual geologic units are described in **Appendix A**. The distribution of geologic units reflects several periods of deposition, uplift, erosion, volcanism, and reworking/re-deposition of older units as younger strata. The erosion of rocks exposed in upland areas and re-deposition in the basins is an ongoing process. Accordingly, the stratigraphic sections preserved in interior basin areas are most complete, and stratigraphic sections are less complete to non-existent at higher elevations in the surrounding mountain ranges. In some places Tertiary and Quaternary deposits directly overly Precambrian basement rocks.

4.4 Granite Mountains, Green Mountain, Ferris Mountains, Seminoe Mountains, Shirley Mountains and Freezeout Mountains (Lillegraven and Snoke, 1996; WSGS, 2013)

Together, these Rocky Mountain foreland features form the southern flank of the Sweetwater Arch which extends over 100 miles from the western edge of the Granite Mountains to the eastern Freezeout Mountains. This area separates the Wind River basin from the Great Divide and Hanna basins, and in a general sense connects the southern end of the Wind River Range with the northern Laramie Mountains.

4.4.1 Granite Mountains (Love, 1970; WSGS, 2013)

The *Granite Mountains,* (**Plate 1; Figures 4-1, 4-2**) which consist of massive pink granite shot through with black diabase dikes, form a number of landmarks such as Independence Rock, Devils Gate, Split Rock, and Sweetwater Crossing along the Sweetwater River. The rocks that form these features crop out in bald, stark knobs that stand above light-colored, flat-lying Tertiary aged sedimentary rocks.

The area of the Granite Mountains is unique because it was once a much higher mountain range, similar to other mountains in the state that formed during the Laramide Orogeny. For example, the Crooks-Green-Ferris-Seminoe-Shirley mountain complex that bounds the Granite Mountains on the south has structural features like those found on the flanks of other Laramide mountain ranges in Wyoming; however, the Granite Mountains lack a high central core of Precambrian terrane. Also like other Wyoming mountain ranges, sedimentary basins on both sides of the Granite

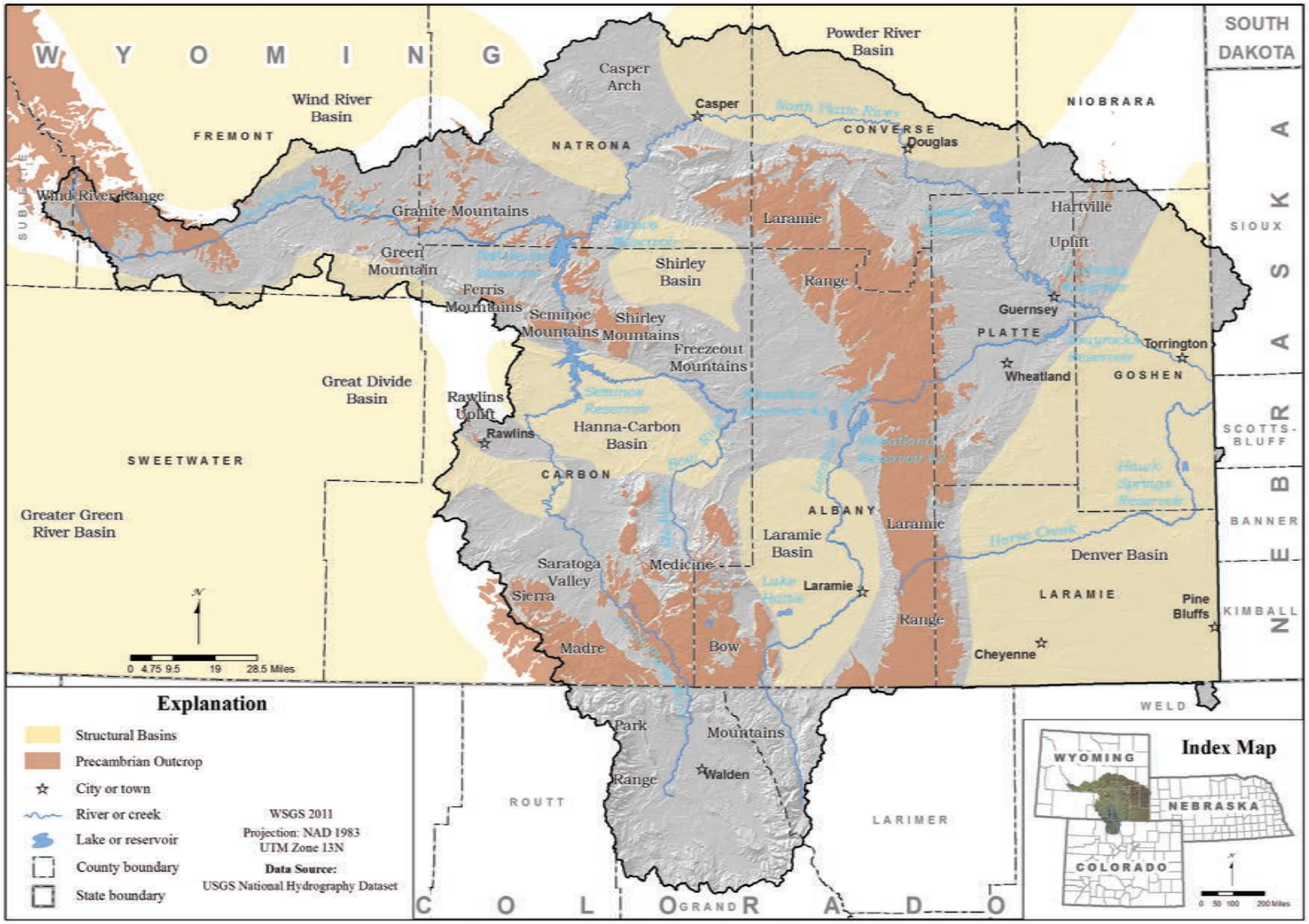
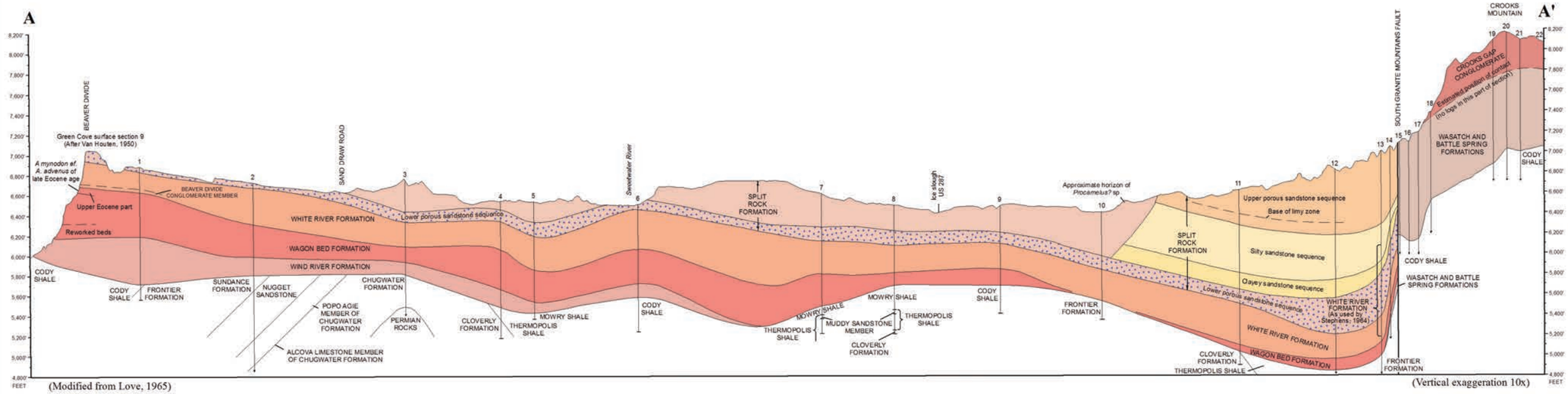
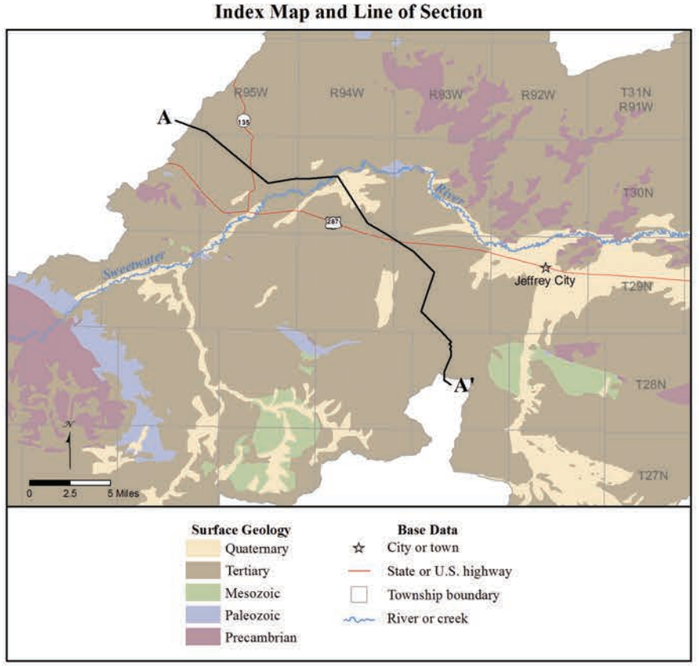


Figure 4-1. Major Laramide structural elements, Platte River Basin.



Index Map and Line of Section



Explanation

Symbols

- Formation contact - dashed where approximately located
- Fault
- Well location and designation

Geologic Units

CENOZOIC
Tertiary

- Split Rock Formation - Upper porous sandstone sequence
- Split Rock Formation - Silty sandstone sequence
- Split Rock Formation - Clayey sandstone sequence
- Split Rock Formation - Lower porous sandstone sequence
- Split Rock Formation undivided
- White River Formation
- Wagon Bed Formation
- Crooks Gap Conglomerate
- Wasatch and Battle Spring Formations
- Wind River Formation

(Data on pre-Tertiary rocks is diagrammatic)

Well Information

Well/Core Hole #	API #	Well/Core Hole Name	Location (Section-Township-Range)	Elevation† (feet)	Depth (feet)	Bottom Formation	Spud Date
1	N/A	Atlantic CH 4	31-31N-95W	6,880	1,320	Frontier	N/A
2	49-013-05252	Govt Sweetwater Crs 1	8-30N-95W	6,737KB	2,835	Permian rocks	1957
3	49-013-05249	California Co. Govt 1	14-30N-95W	6,727KB	2,525	Madison Limestone	1954
4	N/A	Atlantic CH 2	13-30N-95W	6,547	1,354	Cloverly & Morrison, undiff.	N/A
5	49-013-08335	California Co. CH 1	18-30N-94W	6,532	1,159	Mowry Shale	N/A
6	N/A	Sinclair CH 2	16-30N-94W	6,510T	1,260	Cody Shale	N/A
7	49-013-08336	California Co. CH 6	35-30N-94W	6,600T	1,380	Thermopolis Shale	N/A
8	N/A	Sinclair CH 6	36-30N-94W	6,485T	1,270	Cloverly	N/A
9	N/A	California Co. CH 4	5-29N-93W	6,495G	1,072	Cody Shale	N/A
10	N/A	Sinclair CH 1	16-29N-93W	6,415T	1,061	Frontier	N/A
11	N/A	Sinclair CH 10	29-29N-93W	6,635T	1,725	Cloverly	N/A
12	49-013-05223	Govt 33-1	33-29N-93W	6,828KB	4,700	Chugwater	1953
13	49-013-05220	Happy Springs Unit 37	4-28N-93W	6,994KB	7,065	Madison Limestone	1955
14	49-013-05219	Happy Springs Unit 30	4-28N-93W	7,045T	6,378	Permian rocks	1954
15	49-013-05209	Happy Springs Unit 18	4-28N-93W	7,094T	4,527	Cloverly & Morrison, undiff.	1953
16	49-013-05204	Happy Springs Unit 13	4-28N-93W	7,110T	4,632	Cloverly & Morrison, undiff.	1952
17	49-013-05191	Happy Springs Unit 15	9-28N-93W	7,186G	4,760	Cloverly	1952
18	49-013-05177	Happy Springs Unit 28	9-28N-93W	7,391G	4,190	Frontier	1954
19	N/A	Happy Springs Unit 6	8-28N-93W	8,111G	6,625	Thermopolis Shale	N/A
20	49-013-05144	Happy Springs Unit 4	17-28N-93W	8,176G	6,954	Cloverly & Morrison, undiff.	1950
21	49-013-05133	Happy Springs Unit 5	17-28N-93W	8,099G	6,500	Mowry Shale	1951
22	49-013-05129	Happy Springs Unit 3	21-28N-93W	8,064G	6,675	Thermopolis Shale	1950

† T = Topographic Map; KB = Kelly Base on drill rig; G = Ground elevation at well site; no modifier = no data available or unknown
API # and **Spud Date** compiled from Wyoming Oil and Gas Conservation Commission website

Figure 4-2. Geologic cross section A-A'.

Mountains contain a thick sequence of lower Tertiary rocks, including thick conglomerate sequences that become coarser grained as they approach the Granite Mountains. The rock types found in the conglomerates, such as the giant boulders of Precambrian granitic rocks found in and on top of Green and Crooks Mountains south of the Sweetwater River, are exactly the same rock types found in the core of the Granite Mountains. During early Tertiary (Paleocene and especially early Eocene) time, there must have been high mountains in the area to produce these structural features and the conglomerates.

The south and north margins of the Granite Mountains are defined by an obvious system of east-west trending normal faults which preserve late Tertiary sedimentary rocks in the downdropped blocks. These rocks were almost completely removed by erosion elsewhere in Wyoming. At one time, all Wyoming basins were completely filled with these late Tertiary rocks, and only the highest mountain peaks stood above this fill. The granite knobs along the Sweetwater represent the buried crest of the central core of a mountain range that collapsed and subsided in the late Tertiary (mostly in the Pliocene Epoch). It is estimated that at least several thousand feet of the Granite Mountains collapsed along these normal faults into a downthrown trough (graben). This collapse was probably caused by crustal extension that affected other Laramide uplifts as well, but evidently not to the same extent it did the Granite Mountains. The proximity of early Tertiary volcanic rocks of the Rattlesnake Hills on the north edge of the Granite Mountains may also be a factor, and the debate continues as to why this entire mountain range collapsed.

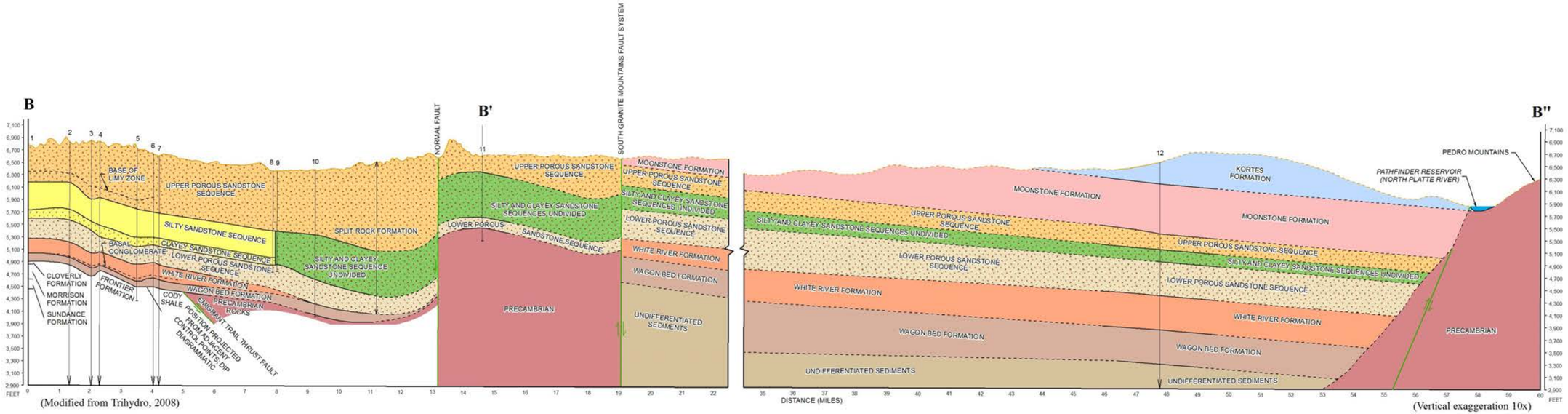
4.4.2 Crooks Mountain, Green Mountain, Ferris Mountains, Seminoe Mountains, Shirley Mountains (Lillegraven and Snoke, 1996)

The geology of these mountains (**Plate 1; Figures 4-1** through **4-3**), which parallel the Granite Mountains to the north, suggests that this structural complex constitutes the remnant of the foothills of the Granite Mountains prior to their collapse. A long system of thrust faults in the west and normal faults in the east, run along the northern flank of this mountain complex and separate it from the Granite Mountains. Crooks Mountain and Green Mountain are both low elevation features composed of Paleocene through Oligocene aged conglomerates containing giant Precambrian granite boulders that have the same composition as the granite knobs of the Granite Mountains.

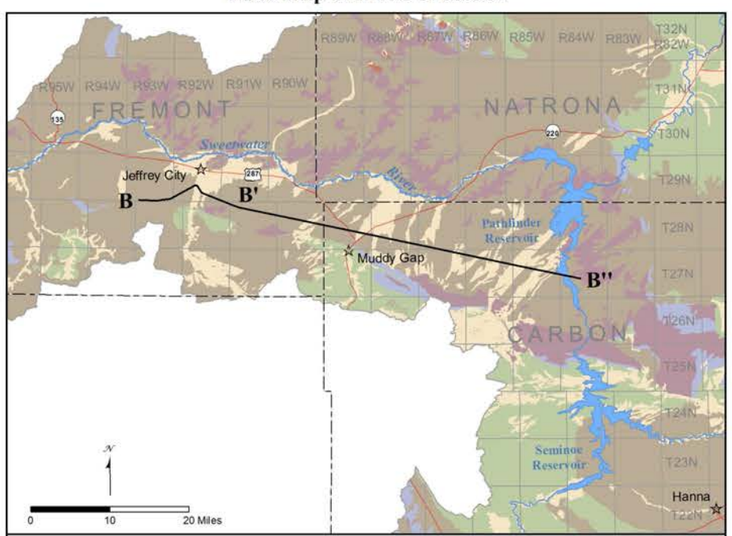
The Ferris Mountains, farther to the east are more rugged and over 2,000 feet higher in elevation. The mountains' flanks consist of an assemblage of upturned Cambrian – Upper Cretaceous sedimentary strata and the Precambrian granite core is exposed along the summit ridge. The most striking geologic features of the Ferris Mountains are the sub vertical exposures of resistant Mississippian Madison Limestone that form the flatirons along its southern flank.

The Seminoe Mountains (elevation 7,421 ft above MSL) have a similar geologic setting to the Ferris Mountains in that Paleozoic and Mesozoic sedimentary units cover its southern flank which also exhibits Madison Limestone flatirons along the mountains eastern half. The Precambrian core is more complex than the granite core of the Ferris Mountains, however. The core of the eastern two thirds of this small mountain range is Late Archean granite while the western third consists of Late Archean metavolcanic and metasedimentary rocks which contain iron and gold ores. Several small gold mines were in operation for a brief period in the late 1800s in this area but no large scale mining operation ever developed.

The Shirley Mountains constitute the easternmost part of the Green Mountains-Ferris Mountains-Seminoe Mountains-Shirley Mountains structural complex, which defines the southern part of the Granite Mountains uplift. The Shirley Mountains contain Precambrian rocks in its western core and a large anticlinal structure involving Paleozoic and Mesozoic rocks in the eastern part. The mountains separate the Shirley Basin to the north from the Hanna Basin to the south. The Shirley Mountains were thrust southward, overriding the deep synclinal axis of the Hanna Basin. The southeastern part of the Shirley Mountains that contains the large anticline draped with Paleozoic and Mesozoic rocks is sometimes called the Freezeout Mountains (or Hills).



Index Map and Line of Section



Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- City or town
- State or U.S. highway
- Township boundary
- County boundary
- River or creek
- Lake or reservoir

Explanation

Symbols

- Fault line
- Ground surface - dashed where inferred
- Formation line - dashed where inferred
- Surface water
- Approximate well location and designation
- Bottom of well
- Indicates depth of well continues beyond limits of cross section
- above mean sea level

Geologic Units

CENOZOIC
Tertiary
- KORTES FORMATION
- MOONSTONE FORMATION
- SPLIT ROCK FORMATION - UPPER POROUS SANDSTONE SEQUENCE
- SPLIT ROCK FORMATION - SILTY AND CLAYEY SANDSTONE SEQUENCES UNDIVIDED
- SPLIT ROCK FORMATION - SILTY SANDSTONE SEQUENCE
- SPLIT ROCK FORMATION - CLAYEY SANDSTONE SEQUENCE
- SPLIT ROCK FORMATION - LOWER POROUS SANDSTONE SEQUENCE

Tertiary (cont.)
- WHITE RIVER FORMATION
- WAGON BED FORMATION
- UNDIFFERENTIATED SEDIMENTS

PRECAMBRIAN
- PRECAMBRIAN ROCKS

Well Information

Well/Core Hole #	API #	Well/Core Hole Name	Location (Section-Township-Range)	Elevation† (feet)	Depth (feet)	Bottom Formation	Spud Date
1	N/A	Sinclair, CH 19	32-29N-93W	6,780 T	2,326	Sundance	N/A
2	49-013-05223	Govt 33-1	33-29N-93W	6,828 KB	4,700	Chugwater	1953
3	49-013-05224	Govt 34-1	34-29N-93W	6,865 G	3,153	Cloverly & Morrison, undiff.	1953
4	49-013-05225	Govt 2	34-29N-93W	6,840 T	3,035	Cloverly & Morrison, undiff.	1956
5	49-013-60025	Sinclair, CH 6-B	35-29N-93W	6,738 G	2,470	Frontier	1956
6	49-013-08381	Sinclair, CH 4-B	36-29N-93W	6,640 T	2,620	Frontier	1956
7	49-013-08380	Sinclair, CH 2-B	36-29N-93W	6,615	2,660	Frontier	1956
8	N/A	Sinclair, CH 5-A	21-29N-92W	6,372 T	1,635	Split Rock	N/A
9	N/A	Sinclair, CH 5	21-29N-92W	6,375 T	1,635	Split Rock	N/A
10	N/A	Sinclair, CH 25	27-29N-92W	6,390 T	2,378	Precambrian	N/A
11	49-013-60062	Split Rock 1	5-28N-91W	6,620 T	1,350	Precambrian	1955
12*	49-007-07151	Test Boring SR-2	9-27N-86W	6,555 GPS	3,820	N/A	N/A

† T = Topographic Map; KB = Kelly Base on drill rig; G = Ground elevation at well site; GPS = Global Positioning System; no modifier = no data available or unknown
API # and Spud Date provided by Wyoming Oil and Gas Conservation Commission
* Data (except API #) from 2008 Split Rock Groundwater Development Project by Trihydro

Figure 4-3. Geologic cross section B-B'-B".

4.5 Hanna-Carbon Basin and surrounding mountain ranges (Richter, 1981; WSGS, 2013)

This sedimentary basin consists of the larger Hanna Basin (**Plate 1; Figures 4-1, 4-4**) and the smaller, subsidiary Carbon Basin to the southeast, separated by the Simpson Ridge anticline. This basin is sandwiched between the Seminoe and Shirley Mountains to the north, the Medicine Bow Mountains to the south, and the Rawlins uplift to the west. It is separated from the Laramie Basin to the southeast by several folds in Cretaceous rocks. The Hanna Basin is quite small as intermontane basins go—only about 35 miles long by 20 miles wide—but it is unique because of the great depth to which the sedimentary rocks are depressed. The Precambrian floor beneath the sedimentary rocks in the deepest part of the basin north of Hanna lies approximately 30,000 feet below sea level. Structural relief ranges from 38,000 feet, measured from the highest point on the Shirley Mountains, to more than 41,000 feet, measured from the top of Elk Mountain (a horizontal distance of only 15 or 20 miles to the deepest part). The basins contain a thick sequence (up to 23,000 feet) of Upper Cretaceous and Tertiary clastic sedimentary rocks derived in part from adjacent uplands. Tertiary rocks in the northern part of the basin adjacent to the Shirley Mountains include a 10,000- to 15,000-foot-thick succession of vertically dipping conglomerates containing clasts eroded from nearly every sedimentary and Precambrian rock exposed in the surrounding uplifts. Overall, the thickness of the sedimentary section ranges up to 35,000 feet (Richter, 1981).

The structure of the Hanna-Carbon Basin is complex. Even the Tertiary rocks that are relatively flat lying in most other Wyoming basins are complexly folded and faulted, especially on the edges of the basin. Only the western part of the basin is relatively undeformed, with the rocks dipping eastward off the Rawlins uplift. Near Hanna, where the basin is deepest, even the youngest (Eocene) part of the Hanna Formation is folded into a small syncline. In the northern part of the basin, Upper Cretaceous rocks are highly overturned and overlain unconformably by lower Tertiary rocks that may also have steep dips.

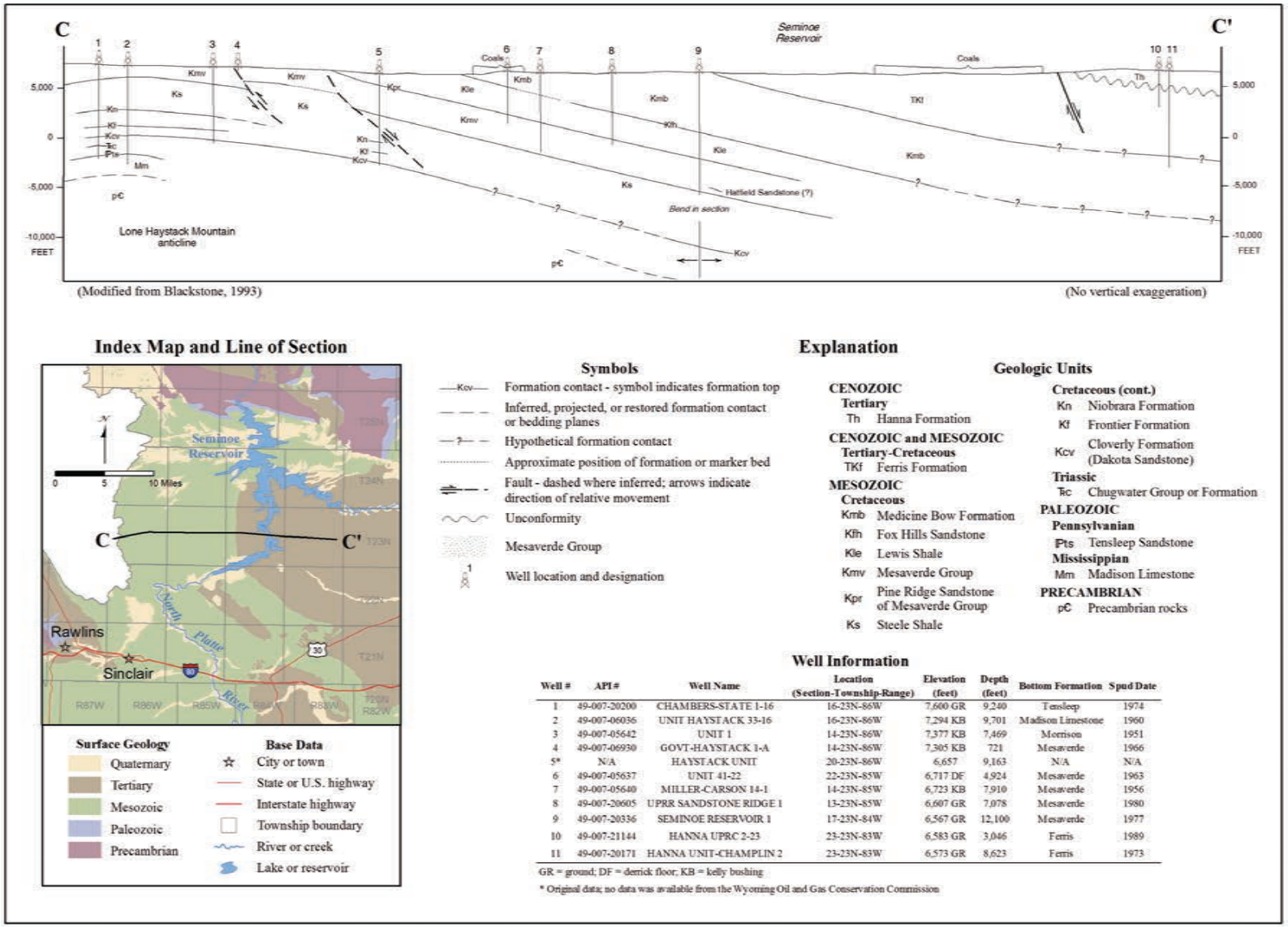
The Tertiary Hanna and Ferris formations contain thick coal beds in both the Hanna and Carbon basins. Coal was originally mined underground at old Carbon (now a ghost town) and later at Hanna, and was used to fuel steam locomotives on the Union Pacific Railroad. After the railroads switched from coal-fired to diesel-electric locomotives, coal mining practically ceased in the basin. Coal mining by both underground and surface methods resumed in the 1970s due to increased demand for coal to fuel electric power plants (brought about by passage of the Federal Clean Air Act). Today, most coal mining activity in the basin has once again nearly ceased because this coal must compete with the easily mined and much cheaper coal from the Powder River Basin.

4.6 Casper Arch (WSGS, 2013)

A structural arch represents a transitional area between Wyoming's basins and mountains. It is primarily an uplifted area, but the extent of uplift has not been enough to form a mountain range with an exposed core of Precambrian basement rocks. Relief is usually about the same as in the adjacent basins, but the uplift has exposed rocks older than those in the basins. The Casper arch (**Plate 1; Figures 4-1, 4-5**) is a large, northwest-trending asymmetric anticlinal structure that connects the Bighorn Mountains with the Laramie Mountains and separates the Powder River Basin (to the northeast) from the Wind River Basin (to the southwest). Rocks on the northeast flank dip gently into the Powder River Basin while steeply dipping rocks are thrust southwestward, overriding the synclinal axis of the Wind River Basin. Upper Cretaceous marine shale crops out in the center of the arch, with rocks as young as Paleocene on the flanks of the arch. Several large oil fields are found on the arch, including the Salt Creek/Teapot Dome, Pine Mountain/Poison Spider, and Tisdale Mountain anticlines, which expose older Cretaceous rocks in their cores.

4.7 Shirley Basin (WSGS, 2013)

The Shirley Basin (**Plate 1; Figures 4-1, 4-6**) is a small relatively undeformed depression



Well #	API #	Well Name	Location (Section-Township-Range)	Elevation (feet)	Depth (feet)	Bottom Formation	Spud Date
1	49-007-20200	CHAMBERS-STATE 1-16	16-23N-86W	7,600 GR	9,240	Tensleep	1974
2	49-007-06036	UNIT HAYSTACK 33-16	16-23N-86W	7,294 KB	9,701	Madison Limestone	1960
3	49-007-05642	UNIT 1	14-23N-86W	7,377 KB	7,469	Morrison	1951
4	49-007-06930	GOVT-HAYSTACK 1-A	14-23N-86W	7,305 KB	721	Mesaverde	1966
5*	N/A	HAYSTACK UNIT	20-23N-86W	6,657	9,163	N/A	N/A
6	49-007-05637	UNIT 41-22	22-23N-85W	6,717 DF	4,924	Mesaverde	1963
7	49-007-05640	MILLER-CARSON 14-1	14-23N-85W	6,723 KB	7,910	Mesaverde	1956
8	49-007-20605	UPRR SANDSTONE RIDGE 1	13-23N-85W	6,607 GR	7,078	Mesaverde	1980
9	49-007-20336	SEMINOE RESERVOIR 1	17-23N-84W	6,567 GR	12,100	Mesaverde	1977
10	49-007-21144	HANNA UPRC 2-23	23-23N-83W	6,583 GR	3,046	Ferris	1989
11	49-007-20171	HANNA UNIT-CHAMPLIN 2	23-23N-83W	6,573 GR	8,623	Ferris	1973

Figure 4-4. Geologic cross section C-C'.

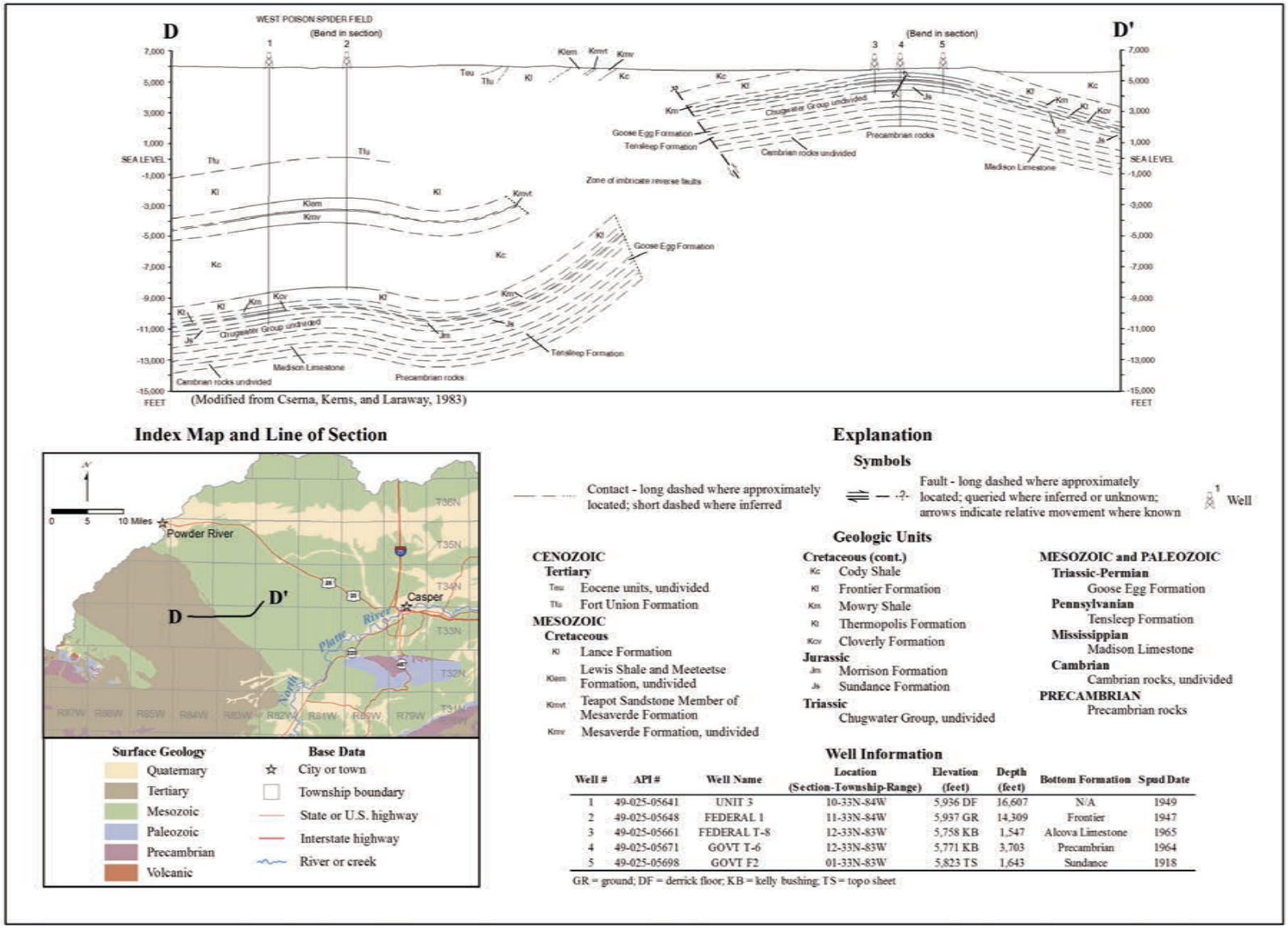
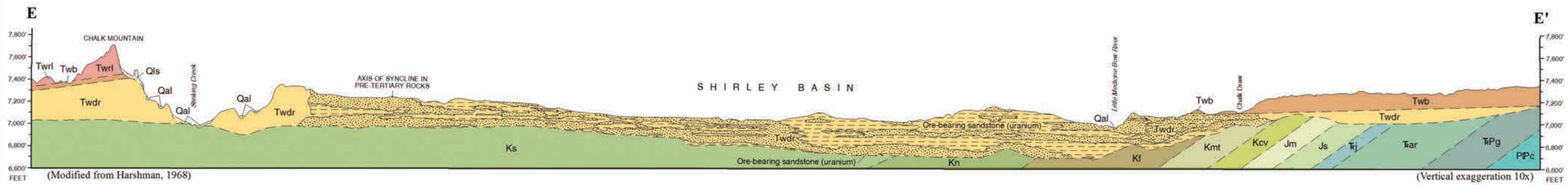
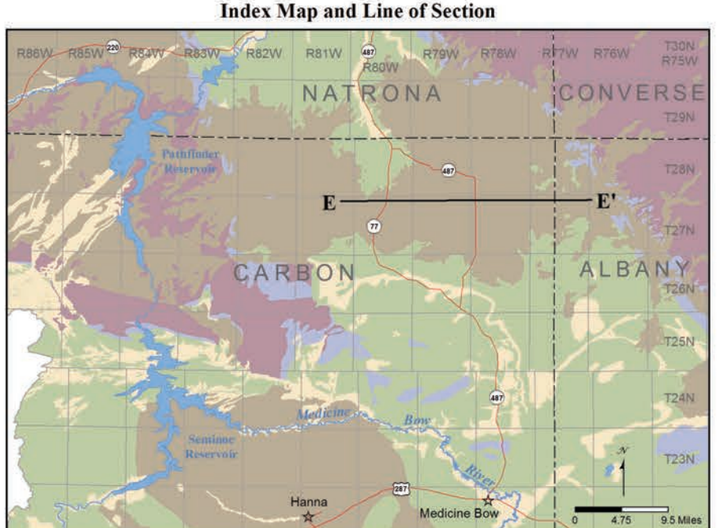


Figure 4-5. Geologic cross section D-D'.



Index Map and Line of Section



Explanation

Lithology

- Sandstone and (or) conglomerate
- Shale or siltstone

Symbols

- Formation contact - dashed where approximately located

Geologic Units

CENOZOIC

Quaternary

- Qal — Alluvium
- Qls — Landslide debris

Tertiary

- Twrl — White River Formation, lower member
- Twb — Wagon Bed Formation
- Twdr — Wind River Formation

MESOZOIC

Cretaceous

- Ks — Steele Shale
- Kn — Niobrara Formation
- Kf — Frontier Formation
- Kmt — Mowry and Thermopolis Shales, undivided
- Kcv — Cloverly Formation

Jurassic

- Jm — Morrison Formation
- Js — Sundance Formation

Triassic

- Tj — Jelm Formation
- Tar — Alcova Limestone and Red Peak Formation, undivided

MESOZOIC and PALEOZOIC

Triassic-Permian

- TPg — Goose Egg Formation

PALEOZOIC

Permian-Pennsylvanian

- PPc — Casper Formation

Figure 4-6. Geologic cross section E-E'.

between the Laramie Range and Freezeout or Shirley Mountains. Its floor is full of flat lying sandstones of the Eocene Wind River formation, which contain large deposits of uranium. Like other uranium deposits in Wyoming, the uranium leached from Precambrian granitic rocks and moved in percolating ground waters into porous sandstones of the Wind River formation. The Shirley Basin contains large reserves of uranium, which are minded from open pits. The north end of the Shirley Basin is covered by white, tuffaceous claystones and sandstones of the Oligocene White River formation, dated at 31 to 35 million years old. The basin contains 8,000 feet of Paleozoic and Mesozoic rock unconformably overlain by a Cenozoic section (Richter, 1981).

4.8 Laramie Basin (Richter, 1981; WSGS, 2013))

Between the Laramie Mountains and the Medicine Bow Mountains is a complexly downfolded area, the trend of which roughly parallels the sweeping arc of U.S. Highway 30 and the Union Pacific Railroad from Laramie to Rawlins. The area is comprised of the Laramie and Hanna-Carbon Basins. The Laramie basin (**Plate 1, Figures 4-1** and **4-7** through **4-11**) is a small (60 miles north to south by 30 mile) trapezoidal shaped asymmetrical Laramide structural basin located in the southern part of this downwarped area. The Laramie Basin is bounded on the northeast and east by the Laramie Mountains, on the south and west by the Medicine Bow Mountains and is open to the northwest. The Laramie Basin contains a maximum thickness 12,000 feet of Cenozoic through Paleozoic sediments near the basin axis.

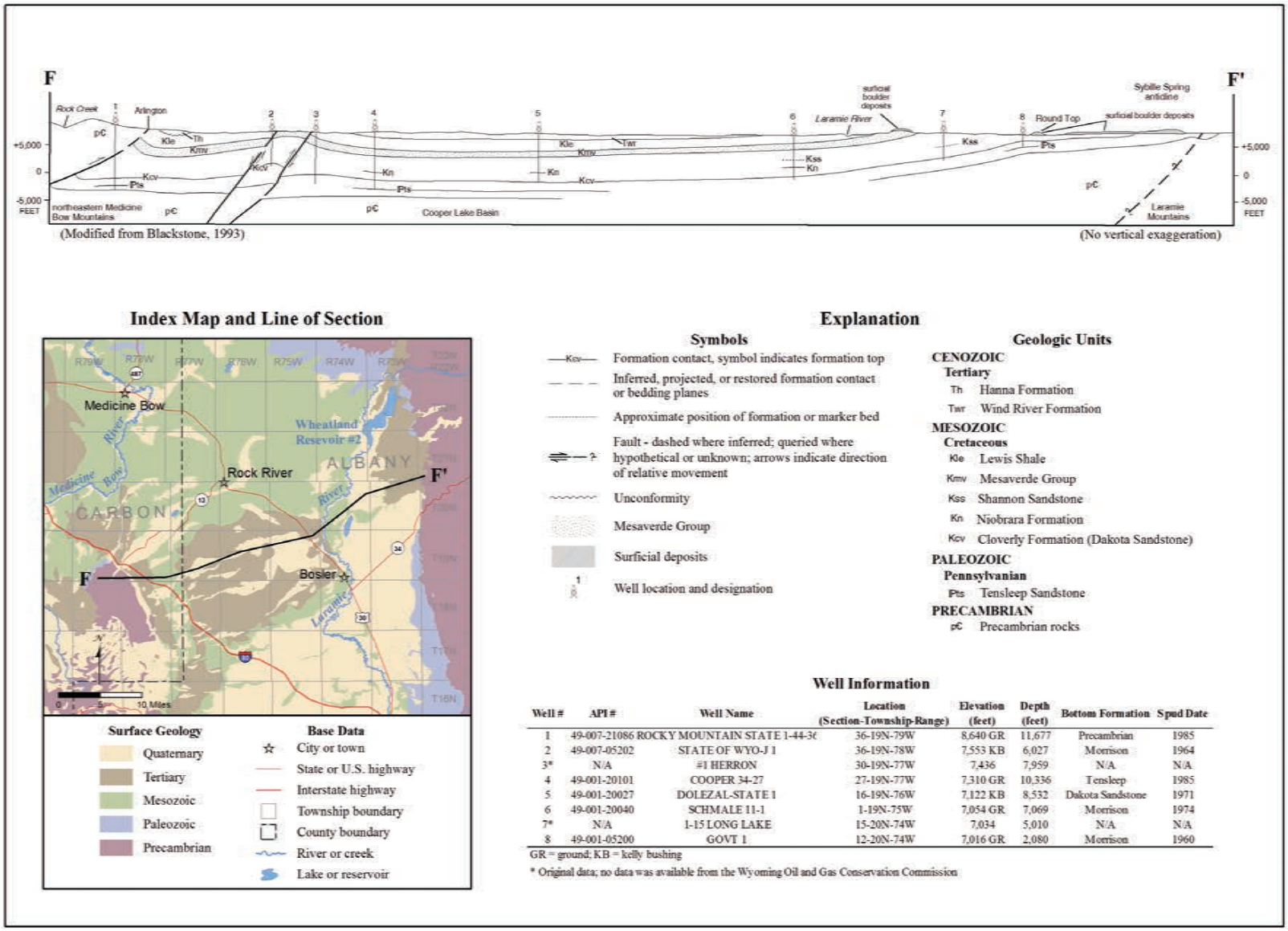
The surface geology consists of nearly horizontal unconsolidated Quaternary deposits which overlay Tertiary units that lie unconformably on Mesozoic and Paleozoic rocks downfolded into a large trough. The structure contour map **(Plate 1, inset)** of the Precambrian basement surface shows that the synclinal axis of the Laramie Basin is located along the west side of the basin and trends generally north-south along the arc of the mountain front of the thrust/reverse faulted Medicine Bow Mountains. Maximum structural relief between the deepest area of the basin and the highest area of the uplifts is about 16,000 feet defined by the difference between elevations in the deepest part of the structural basin, approximately 4,000 feet below sea level and on Medicine Bow Peak at 12,006 feet above sea level in the Snowy Range Mountains (Blackstone, 1993).

4.9 Laramie, Medicine Bow and Sierra Madre Mountain Ranges (WSGS, 2013)

Just south of the Colorado-Wyoming boundary, the mountain masses of the Colorado Front Range of the Southern Rocky Mountains divide into three prongs that extend northward into Wyoming. These three prongs are known, from east to west, as the Laramie Mountains, the Medicine Bow Mountains, and the Sierra Madre. The Laramie Mountains (**Plate 1, Figures 4-1,** and **4-12** through **4-16**) are most closely related to, and are an extension of, the Colorado Front Range. In Wyoming, they separate the Denver Basin and Hartville uplift to the east from the Laramie and Shirley basins to the west. Casper Mountain, a northern salient of the Laramie Mountains, borders the Casper arch on the south. The northeastern Laramie Mountains borders the Powder River Basin on the south.

The *Laramie Mountains* are a moderately high (8,000 – 9500 feet above sea level) mountain range. The high relief landscape in the northern part of the range is capped by Laramie Peak (elevation 10,274 feet), a famous landmark well known to emigrants traveling westward along the Oregon Trail. Farther south, near the border between Wyoming and Colorado, the Laramie Mountains have been reduced by erosion to low relief. The basic geologic structure of the range is of a large asymmetric arch, steepest on the east. Precambrian rocks are extensively exposed in its core, which is flanked by sedimentary strata.

Crossing the Laramie Mountains between Cheyenne and Laramie, Interstate 80 and the Union Pacific Railroad first traverse a relatively flat surface of late Tertiary sedimentary rocks called the "Gangplank," finally reaching the Precambrian core of the mountains and a rolling upland of low relief at about 8,000 feet above sea level called the Sherman surface. The Gangplank



Well Information

Well #	API #	Well Name	Location (Section-Township-Range)	Elevation (feet)	Depth (feet)	Bottom Formation	Spud Date
1	49-007-21086	ROCKY MOUNTAIN STATE 1-44-36	36-19N-79W	8,640 GR	11,677	Precambrian	1985
2	49-007-05202	STATE OF WYO-J 1	36-19N-78W	7,553 KB	6,027	Morrison	1964
3*	N/A	#1 HERRON	30-19N-77W	7,436	7,959	N/A	N/A
4	49-001-20101	COOPER 34-27	27-19N-77W	7,310 GR	10,336	Tensleep	1985
5	49-001-20027	DOLEZAL-STATE 1	16-19N-76W	7,122 KB	8,532	Dakota Sandstone	1971
6	49-001-20040	SCHMALE 11-1	1-19N-75W	7,054 GR	7,069	Morrison	1974
7*	N/A	1-15 LONG LAKE	15-20N-74W	7,034	5,010	N/A	N/A
8	49-001-05200	GOVT 1	12-20N-74W	7,016 GR	2,080	Morrison	1960

GR = ground; KB = kelly bushing

* Original data; no data was available from the Wyoming Oil and Gas Conservation Commission

Figure 4-7. Geologic cross section F-F'.

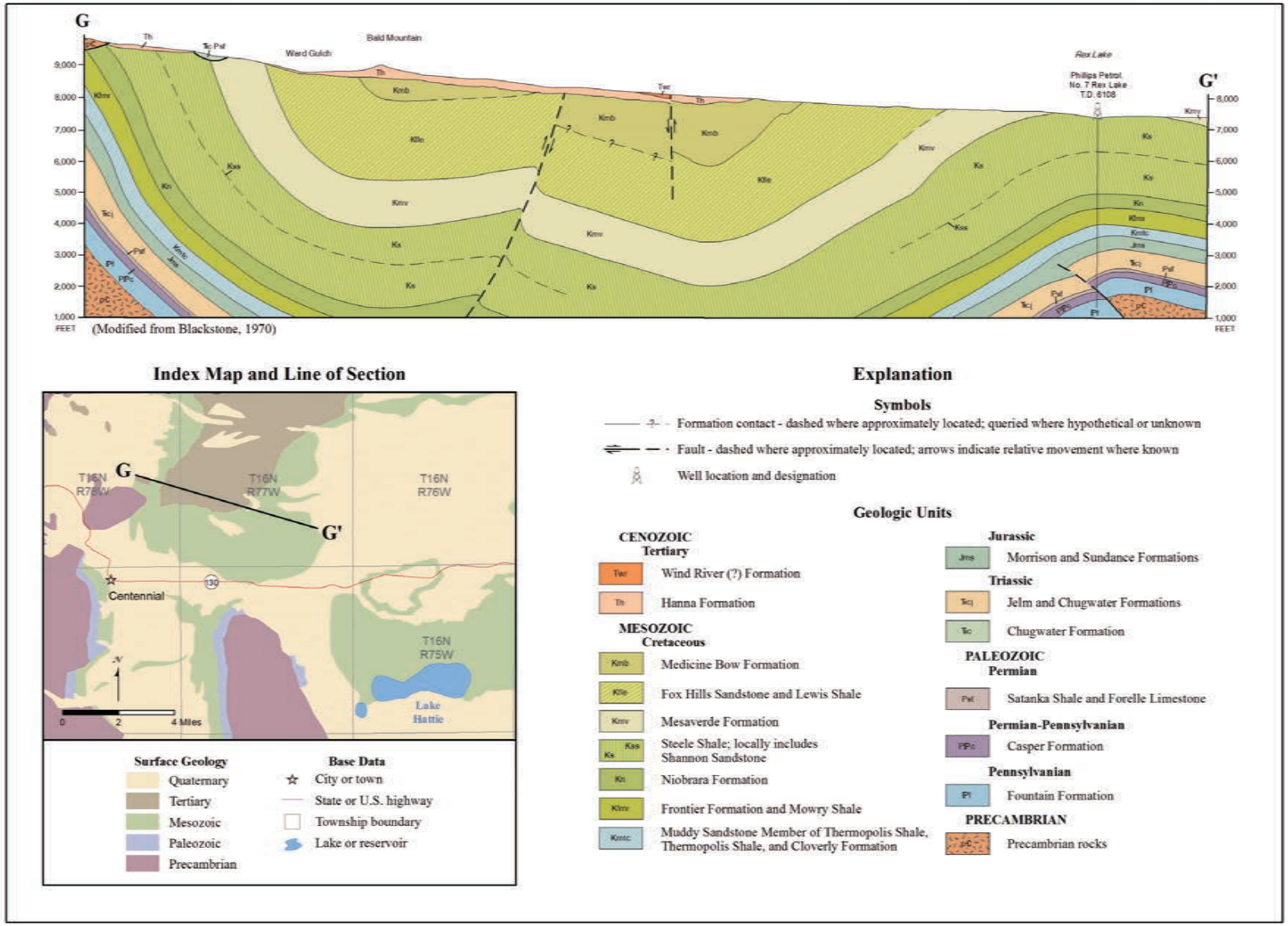


Figure 4-8. Geologic cross section G-G'.

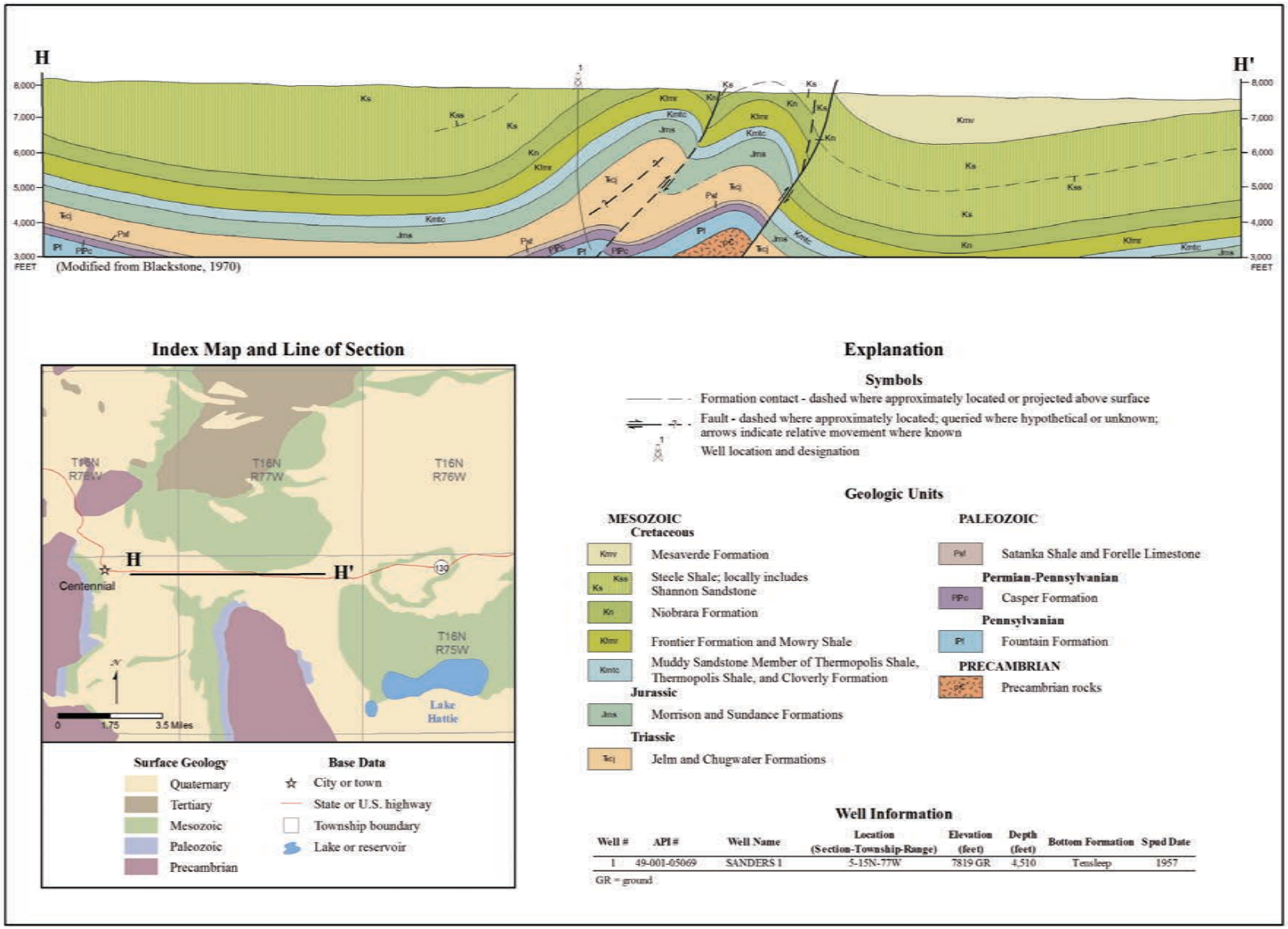


Figure 4-9. Geologic cross section H-H'.

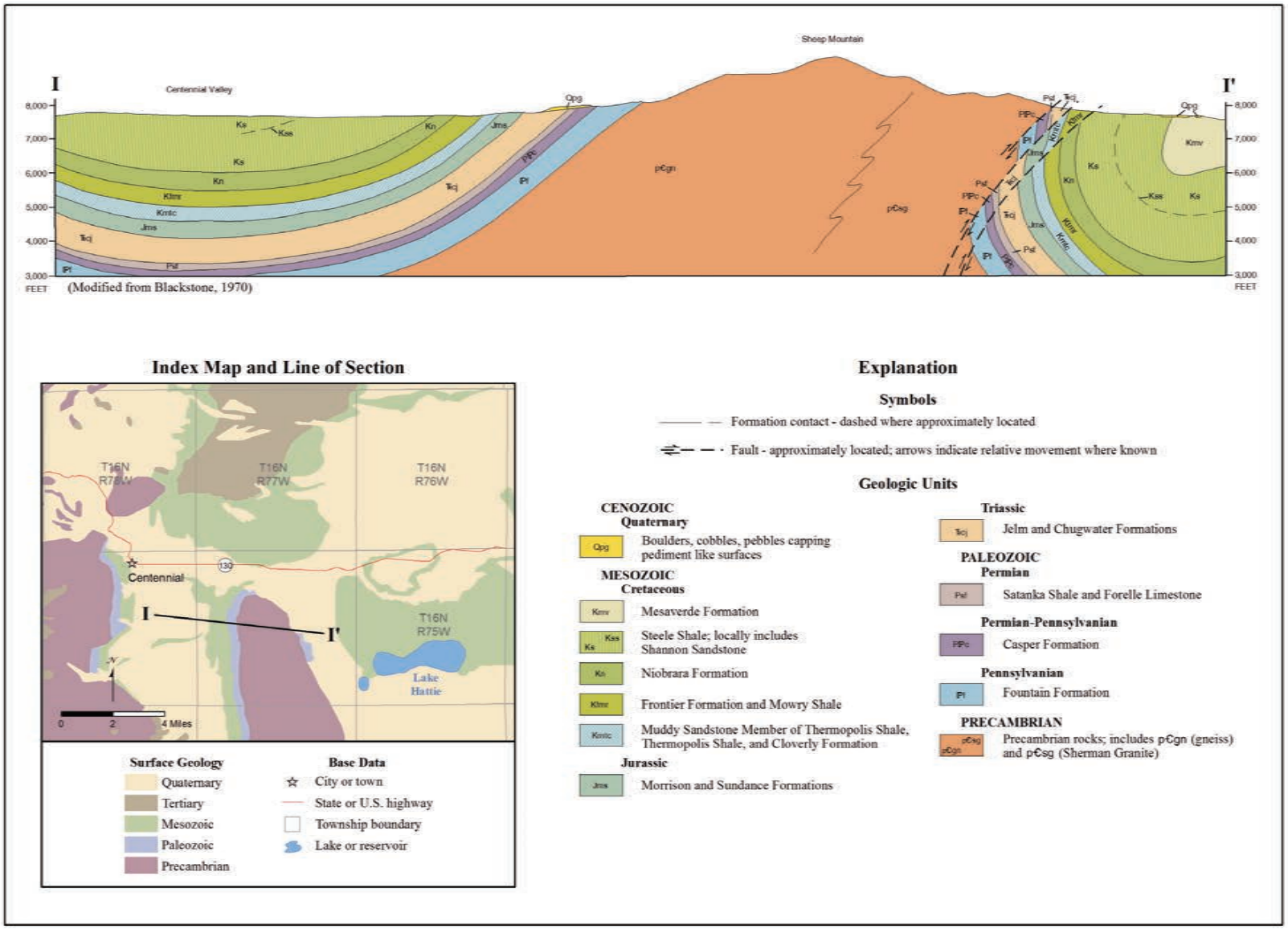


Figure 4-10. Geologic cross section I-I'.

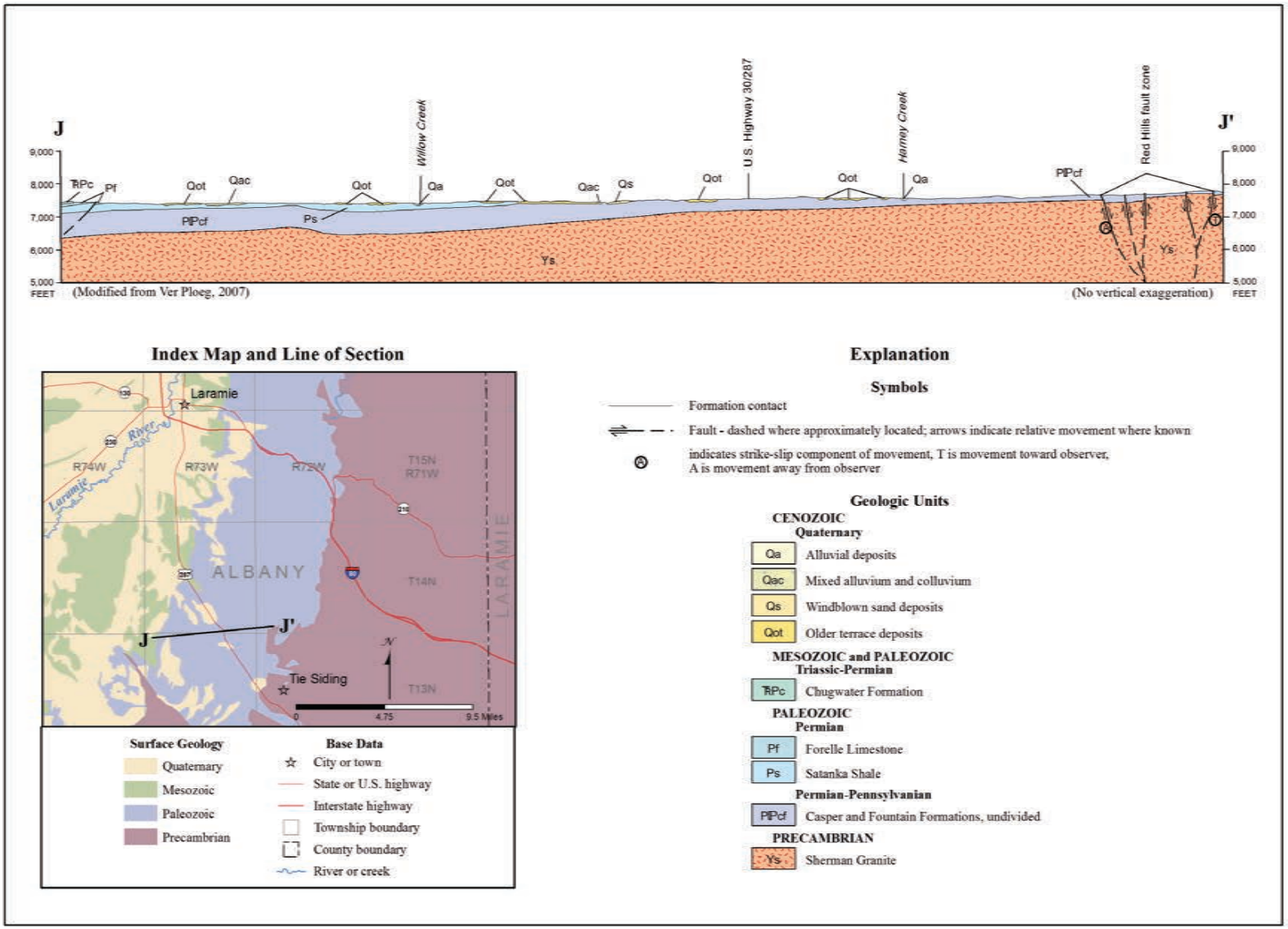


Figure 4-11. Geologic cross section J-J'.

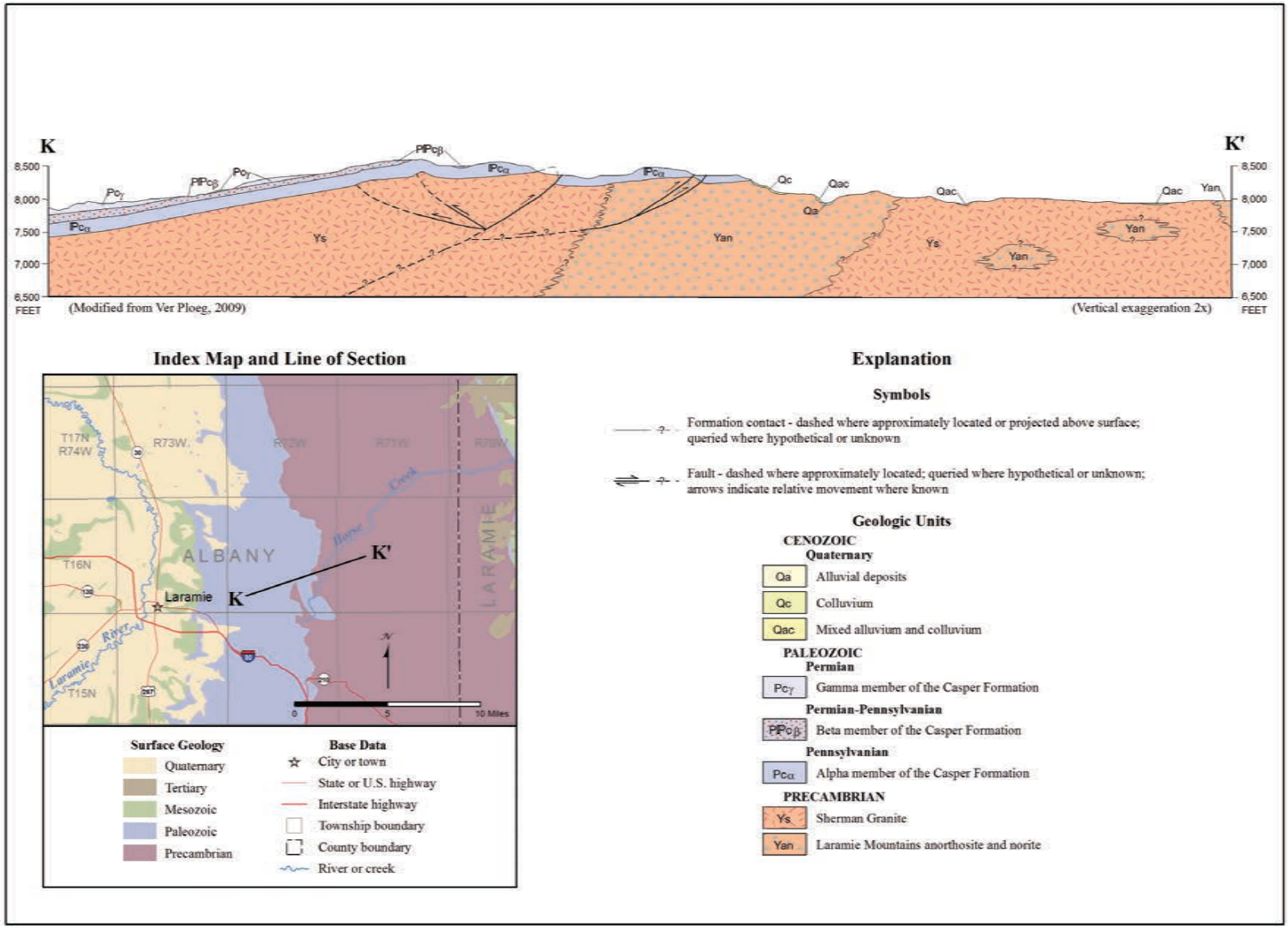


Figure 4-12. Geologic cross section K-K'.

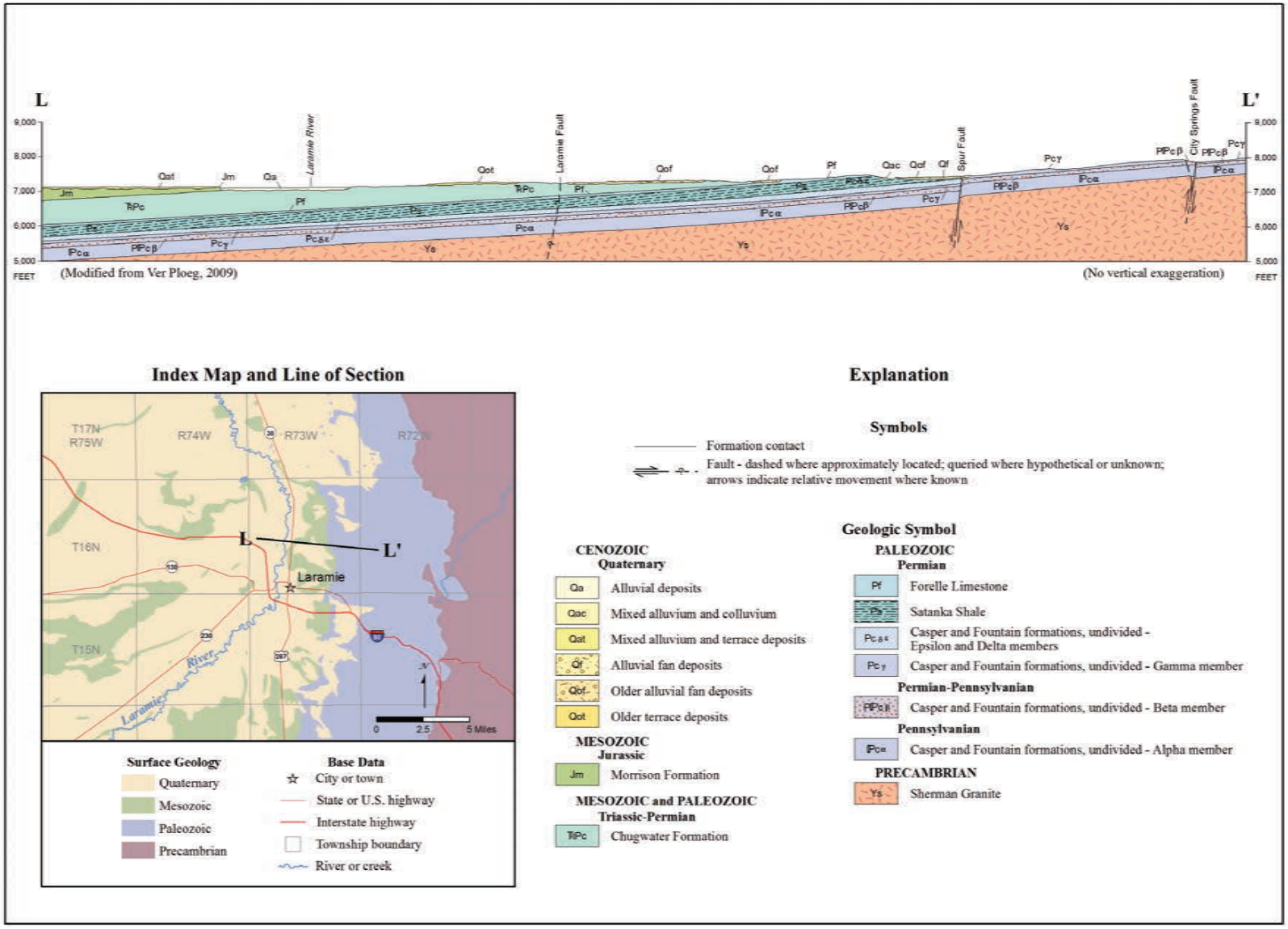


Figure 4-13. Geologic cross section L-L'.

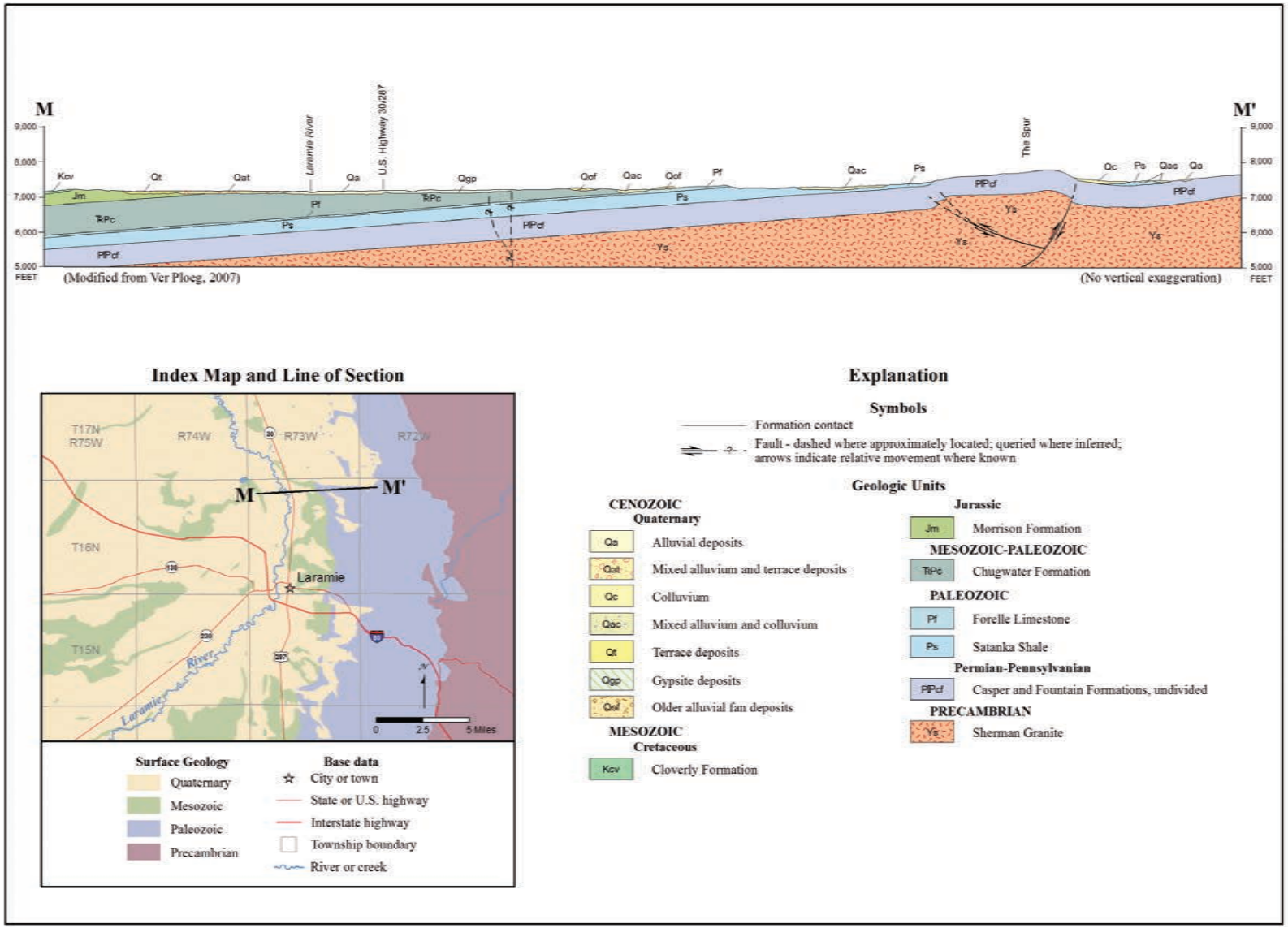


Figure 4-14. Geologic cross section M-M'.

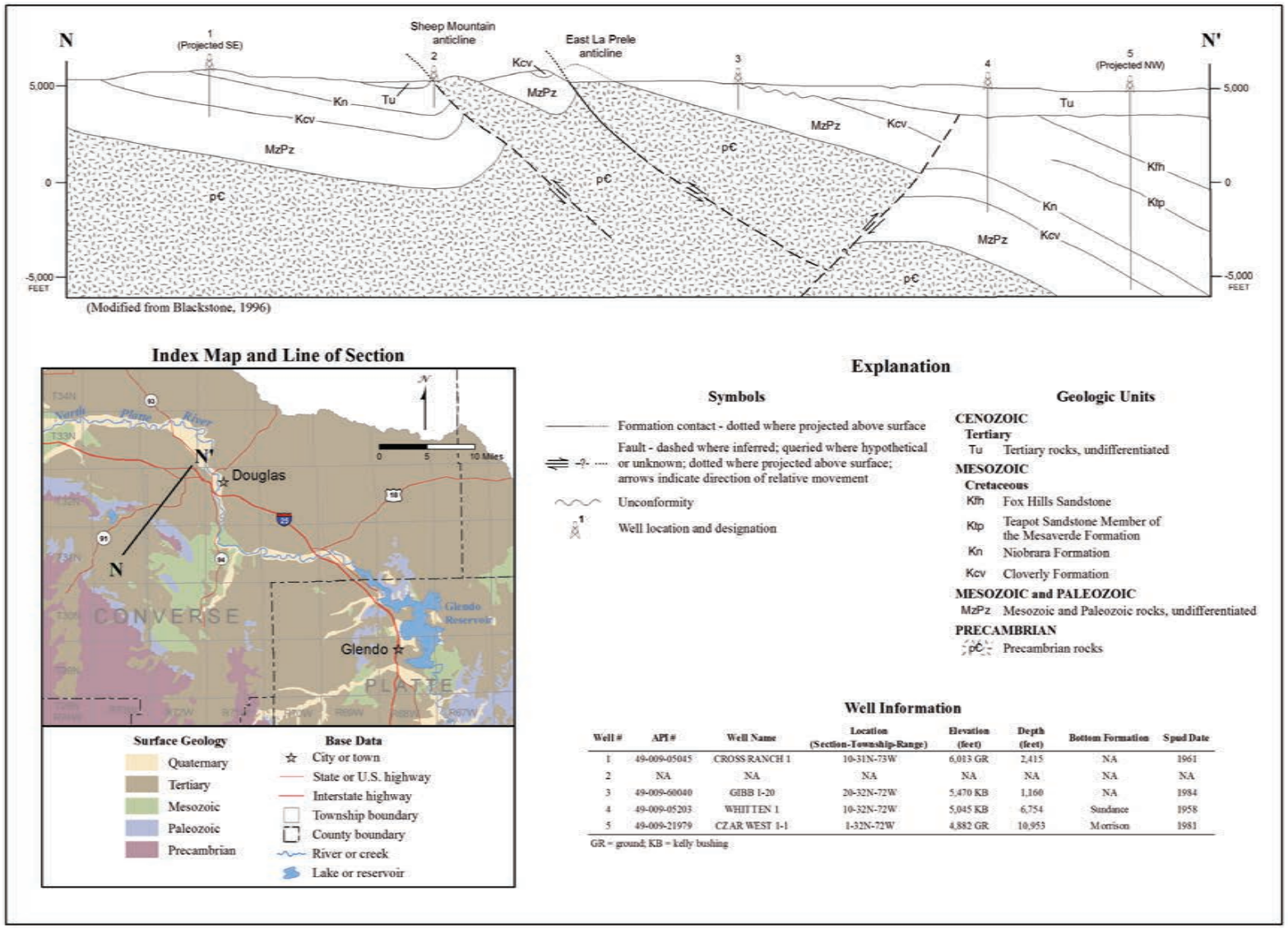


Figure 4-15. Geologic cross section N-N'.

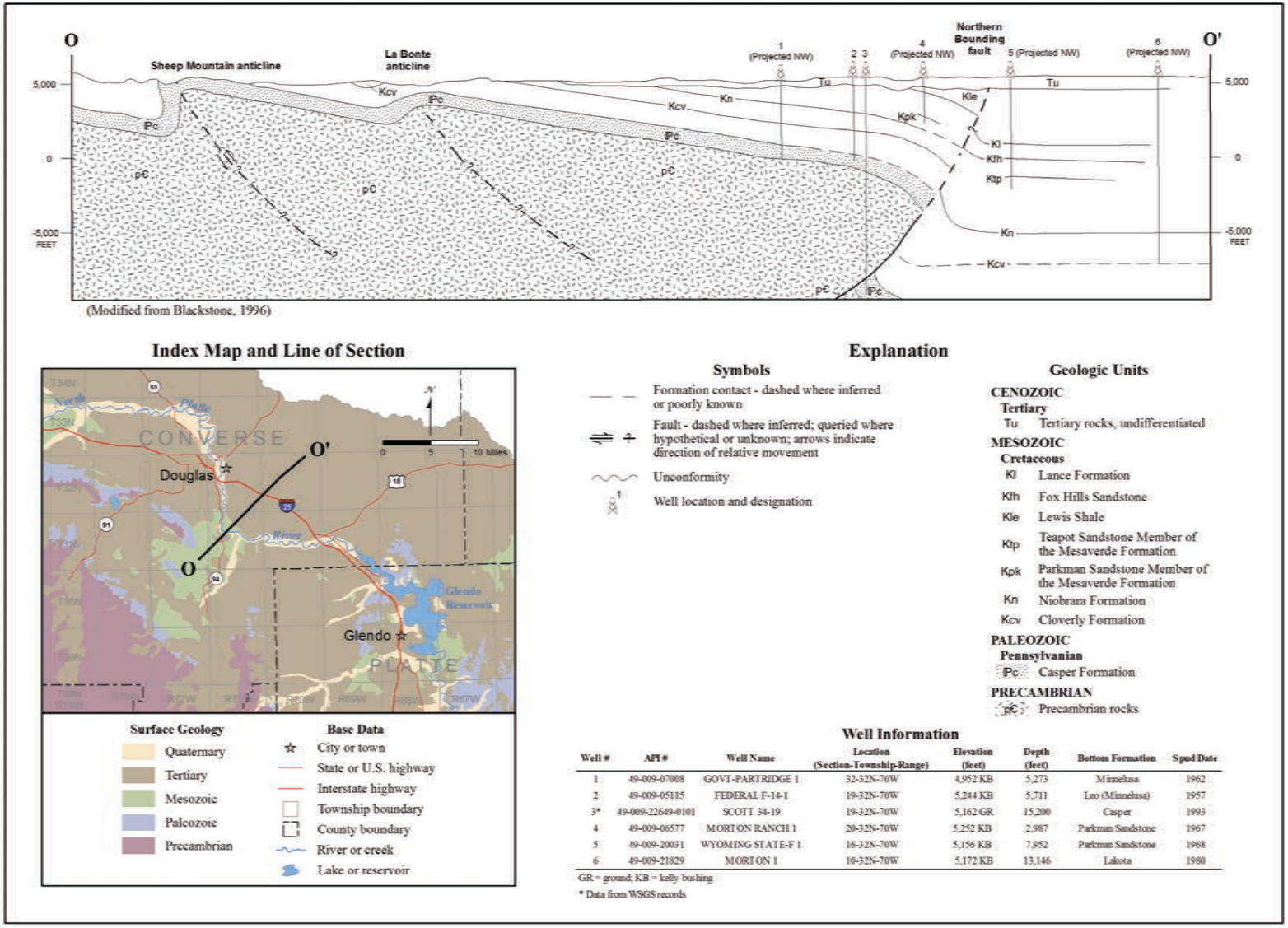


Figure 4-16. Geologic cross section O-O'.

is the only place along the entire eastern mountain front where the Tertiary rocks that once buried the Laramie Mountains are still preserved and are in contact with the Precambrian core of the mountains. Further erosion during later Tertiary time left a few higher granite boulder knobs such as the spectacular area at Vedauwoo. Sherman Pass, at the summit of the Laramie Mountains on Interstate 80, is the highest point (8,640 feet above sea level) on this transcontinental highway. The Pennsylvanian Permian Casper formation outcrops along the western flank of the Laramie Mountains from Sherman Pass to the city limits of Laramie and its heavily fractured alternating limestone-sandstone strata can be seen in the road cuts along I-80.

The Medicine Bow Mountains are the middle prong of the Front Range that projects into Wyoming, and the northward extension of the Never Summer Range in Colorado. This mountain range is separated from the Laramie Mountains by the Laramie Basin, a structural basin underlying the Laramie plains. The mountains are characterized by a rather broad, rolling upland surface approximately 9,000 feet above sea level, above which rise two areas of higher relief. The highest part of the Medicine Bow Mountains, the Snowy Range, consists of a thick sequence of metasedimentary rocks, including a thick, very resistant white quartzite that culminates in Medicine Bow Peak at 12,006 feet.

The Medicine Bow uplift contains an excellent geologic record of two major ages of Precambrian rocks in the western United States: the older Archean (more than 2.5 billion years old) and the younger Proterozoic (2.5 billion to 540 million years old). A thick series of Proterozoic metasedimentary rocks is in fault contact along a major shear zone (or suture) with an older sequence of Archean-age metamorphic rocks. Stromatolites occur within 1.7 billon-year-old metasedimentary rocks. Stromatolites are fossil remains of blue-green algae, among the oldest and earliest forms of life known. They resemble giant cabbage heads and can be seen along the road to Lewis Lake en route to the Sugarloaf Recreation Area.

The *Sierra Madre* is the name applied in Wyoming to a section of mountainous terrain that is continuous with a mountain mass in Colorado called the Park Range. The Sierra Madre Range is the western prong of the Colorado Front Range that projects into Wyoming. This uplift separates the Saratoga Valley from the Washakie Basin, and may be structurally connected to the Rawlins uplift to the north. The Continental Divide runs along the crest of the Sierra Madre, and the highest point is Bridger Peak (11,007 feet). Drainages on its west flank flow to the Colorado River by way of the Little Snake River; drainages on its east flank flow to the North Platte River.

Geologically, the Sierra Madre are quite similar to the Medicine Bow Mountains, but lack the broad upland surface of the latter. The same major shear zone (or suture) that cuts across the Medicine Bow Mountains is also present in the Sierra Madre. This suture, called the Cheyenne belt, separates the oldest Archean rocks of what is known as the Wyoming Province to the north from younger igneous and metamorphic rocks to the south. Attached to the rocks north of the Cheyenne belt are some younger Early Proterozoic metasedimentary rocks similar to those in the Medicine Bow Mountains to the east. The Archean rocks of the Wyoming Province extend northward from the Sierra Madre to form the Precambrian cores of nearly all Wyoming mountain ranges. South of the Cheyenne belt in the Sierra Madre are well-preserved metamorphosed volcanic and sedimentary rocks (including basalt, andesite, and rhyolite flows and tuffaceous rocks, shales, and greywackes), as well as some younger granitic intrusions approximately 1.7 and 1.4 billion years old.

4.10 Rawlins Uplift (WSGS, 2013)

The Rawlins Uplift defines the eastern margin of the Great Divide Basin, the western end of southeastern Wyoming, and the beginning of the desert basin of the west. It is a small Laramide Uplift that has many of the characteristics of larger Wyoming ranges. Precambrian basement rocks are exposed in the core of the uplift, and its flanks are composed of outwardly-dipping Paleozoic and Mesozoic strata. A thrust fault dips beneath the uplift along the west and south sides. Rawlins lies at its south end.

4.11 Saratoga Valley (WSGS, 2013)

This area is a northwest-trending structural low between uplifts of the Medicine Bow Mountains to the east and the Sierra Madre to the west. The North Platte River flows north through this valley. Rocks of Miocene age overlie (or are faulted against) Precambrian rocks in the southern Saratoga Valley near the Colorado border and progressively truncate Paleozoic and lower Mesozoic rocks in the subsurface to the north. Upper Cretaceous rocks crop out in the northern Saratoga Valley and form a small sub-area known as the Kindt Basin. The east-trending Grenville Dome and Fort Steele anticlines on the northern flank of the Kindt Basin approximately define the northern boundary of the Saratoga Valley, separating it from the Hanna Basin to the north, while the Rawlins uplift and Miller Hill anticline (the northern projection of the Sierra Madre) bound the valley to the northwest.

4.12 Great Divide Basin, Wind River Basin, Powder River Basin (WSGS, 2013)

The Platte River Drainage Basin contains small portions of the northern Great Divide, southeastern Wind River, southwestern Powder River and northeastern Green River structural basins. The Green River and Great Divide structural basins constitute two subbasins within the Greater Green River Basin.

4.12.1 Great Divide Basin

Geologically, the *Great Divide Basin* is one of the two eastern sub-basins within the Greater Green River Basin. It is bounded on the east by the Rawlins uplift; on the north by the Granite Mountains (and related Crooks Mountain-Green Mountain uplifts) and the southern Wind River Range; and on the west by the north plunge of the Rock Springs uplift. The deepest part of the basin lies along the steep east flank of the Rawlins uplift and the northern mountains. The Great Divide basin contains a thick sequence of marine Upper Cretaceous and continental early Tertiary rocks as well as lacustrine rocks related to the Eocene Green River Formation. A thick, early Eocene arkosic conglomerate called the Battle Spring Formation crops out in the northeast third of the basin and interfingers with finer-grained rocks in the rest of the basin. This conglomerate was derived from the Granite Mountains that once stood high above the northern part of the basin. The maximum thickness of the sedimentary units in that part of the Great Divide Basin located within the Platte River watershed exceeds 29,000 feet (Blackstone, 1993).

Because of its location at the top of the continent, and the fact that no high mountain masses exist to the west or the east, the Great Divide Basin presents no restriction to the westerly airflow pattern of western North America. This westerly flow is "funneled" through southwestern Wyoming between the mountain masses of the Overthrust Belt/Wind River Range in Wyoming and the Wasatch/Uinta mountains in Utah. In other words, the wind blows, and it blows a lot, in this part of Wyoming. Because southwestern Wyoming is a desert environment and many of the outcropping rocks are poorly consolidated and easily eroded, it is no coincidence that the Great Divide Basin is home to extensive sand dune fields. For example, the Killpecker dune field, which extends across the Great Divide Basin from near Farson to Seminoe and Pathfinder Reservoirs, is the largest continuous area of active sand dunes in the U.S. In the Platte River Basin, the Killpecker dune field extends eastward from the south side of Green Mountain across the northern Great Divide basin to Seminoe Reservoir, passing along the south side of the Ferris Mountains and Seminoe Mountains. Another arm of the dune field runs northeast past the west end of the Seminoe Mountains to Pathfinder Reservoir. Surrounding the areas of active sand dunes are even larger areas of stabilized or inactive dunes.

4.12.2 Wind River Basin

Almost exactly in the center of Wyoming is a rhomboidal topographic depression known as the Wind River Basin (**Plate 1, Figure 4-5**). Mountains and uplifts surround the basin, and nothing about the area is simple. The east and west sides of the rhomb are bounded by the northwest-

trending Casper arch and Wind River Mountains, respectively; the north side is bounded by the Bridger-Owl Creek-Washakie ranges; and the south side is bounded by the Granite Mountains. In general, the basin is a highly asymmetrical syncline, with the basin axis nearest and parallel to the northern mountains and the Casper arch. The deepest part of the trough lies in the north, immediately adjacent to the Owl Creek Mountains, where the Precambrian basement may be displaced vertically more than 30,000 feet. The maximum thickness of the sedimentary units in that part of the Wind River Basin located within the Platte River watershed is nearly 24,000 feet (Blackstone, 1993) and occurs farther to the southeast along the basin axis.

The western boundary of the basin is the east-dipping flank of the Wind River Range, characterized by northwest-trending hogbacks of Paleozoic sedimentary rocks. Structurally, the southern boundary is the northern flank of the Granite Mountains, defined by a series of northwest-trending features including the Rattlesnake Hills, Conant Creek, and Alkali Butte anticlines. These anticlines lie north of the North Granite Mountains fault system. Topographically, most of the southern boundary is a north-facing escarpment of Middle Eocene, Oligocene, and Miocene rocks known as Beaver Rim and Shirley Rim, an erosional feature analogous to the Pine Ridge escarpment in eastern Wyoming and Nebraska.

The Casper arch, a broad upfold of sedimentary rock, forms the eastern boundary. Topographic relief is low, but the rocks are greatly elevated relative to their depth in the Powder River and Wind River Basins on opposite sides of the arch. Exploratory drilling revealed that the west side of the arch is in the hanging wall of a thrust fault with low dip to the east. There is more than 5 miles of westward movement on this hanging wall, and the fault has actually overridden the synclinal axis of the Wind River Basin. Oil and gas production in deep reservoirs has been established in the footwall of this thrust fault.

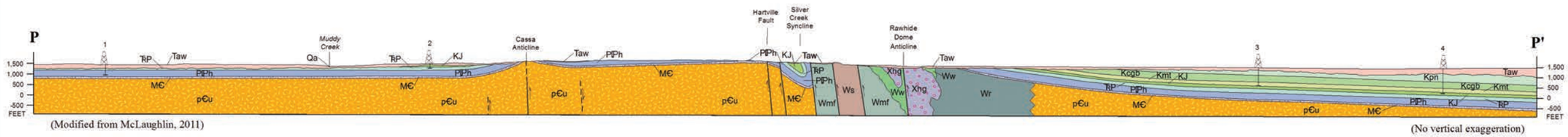
The first oil well in Wyoming was drilled southeast of Lander at Dallas Dome in 1884, and oil has been produced from this and a series of northwest-trending anticlines along the western and northwestern edges of the basin ever since. Extensive oil and gas development has occurred in nearly all parts of this basin, and reservoirs of nearly every age have produced. The basin contains a thick sequence of Upper Cretaceous and lower Tertiary sedimentary rocks that contain important reserves of coal, oil, and especially natural gas.

4.12.3 Powder River Basin

A very wide and moderately deep basin, the Powder River Basin (**Plate 1; Figures 4-1** and **4-17**) lies between the Black Hills and the Bighorn Mountains. It is separated from the Wind River Basin by the Casper arch and from the Denver Basin by the Hartville uplift. The basin is asymmetrical, with the steepest dips and the basin axis on the western side of the basin, near and parallel to the eastern Bighorn Mountain front. In several places along the western and southern edges, the basin has been overridden by thrust faults that place Precambrian and Paleozoic rocks against Tertiary rocks of the basin. The maximum thickness of the sedimentary units in that part of the Powder River Structural Basin situated within the Platte River watershed is almost 19,000 feet (Blackstone, 1993).

The basin edges are defined by a relatively thin band of Cretaceous marine sedimentary rocks; the basin interior is characterized by a wide expanse of lower Tertiary rocks, i.e., the Paleocene Fort Union Formation and the Eocene Wasatch Formation. In many places, the natural burning of thick coal beds initiated by lightning strikes, grass fires, and spontaneous combustion has baked the rocks overlying the coal beds in a manner similar to the action of a brick kiln. The resulting baked rock, known variously as clinker, red dog, or scoria, is usually red from oxidation of iron in the sediments; it is more resistant to erosion than the unbaked rocks below, and caps buttes and mesas over a large area of the basin where coal beds are at or near the surface.

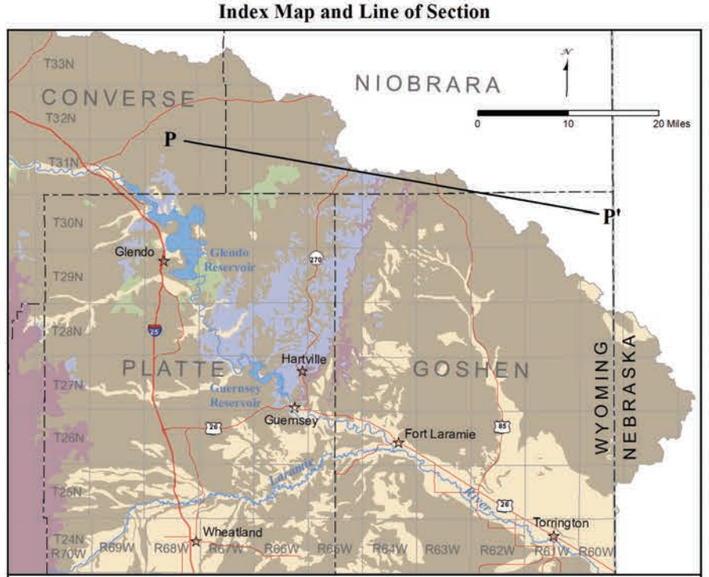
This basin is one of the most important energy-producing areas in Wyoming (and the nation). Its vast coal resources are augmented by oil and natural gas resources, including natural gas produced from coal beds, and uranium deposits. Over broad areas, the Tertiary rocks contain extensive low-sulfur coal



(Modified from McLaughlin, 2011)

(No vertical exaggeration)

Index Map and Line of Section



Surface Geology

- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data

- City or town
- State or U.S. highway
- Interstate highway
- Township boundary
- County boundary
- State boundary
- River or creek
- Lake or reservoir

Explanation

Symbols

- Formation contact
- Fault - dashed where approximately located; arrow indicates relative movement where known
- Well location and designation

Geologic Units

CENOZOIC

Quaternary

- Qa — Alluvial deposits

Tertiary

- Taw — Arikaree and White River Formations, undivided

MESOZOIC

Cretaceous

- Kpn — Pierre Shale and Niobrara Formation, undivided
- Kcgb — Carlile Shale, Greenhorn Formation, and Belle Fourche Shale, undivided
- Kmt — Mowry Shale, Muddy Sandstone, and Thermopolis Shale, undivided

Cretaceous and Jurassic

- KJ — Cloverly, Morrison, and Sundance Formations, undivided

Triassic and Permian

- TRP — Chugwater and Goose Egg Formations, undivided

PALEOZOIC

Permian and Pennsylvanian

- PIPh — Hartville Formation, undivided

Mississippian, Devonian, and Cambrian (?)

- MЄ — Mississippian, Devonian, and Cambrian (?) rocks, undifferentiated

PRECAMBRIAN

- Xhg — Gneissic phase of Haystack Range Granite
- Wr — Rawhide Buttes Granite
- Ww — Wildcat Hills Formation
- Ws — Silver Springs Formation
- Wmf — Mother Featherlegs Metabasalt
- pЄu — Precambrian rocks, undifferentiated

Well Information

Well #	API #	Well Name	Location (Section-Township-Range)	Elevation (Feet)	Depth (feet)	Bottom Formation	Spud Date
1	49-009-22239	PICKINPAUGH 1-6	6-31N-68W	4,806 KB	1,472	Precambrian	1983
2	49-027-07025	BROOKS 1	14-31N-66W	5,112 KB	1,105	Opeche Shale	1951
3	49-015-20031	MARY S MOORE 1	1-30N-62W	4,932 KB	3,116	Morrison	1969
4	49-015-05087	STENGER 1-12	12-30N-61W	4,797 KB	4,239	Chugwater	1956

KB = kelly bushing

Figure 4-17. Geologic cross section P-P'.

deposits that are surface-mined near Gillette and Wright. Most of Wyoming's coal production comes from the Powder River Basin, and the state has been the leading coal producer in the U.S. since the late 1970s. The important Wyoming-type or "roll-front" uranium deposits were discovered at Pumpkin Buttes in the center of the basin in the 1950s, and led to the state's uranium boom.

4.12.4 Green River Basin (WSGS, 2013)

This is a large, complex intermontane area that covers much of southwestern Wyoming; it is used as a general term to include a number of separate structural arches and sedimentary basins as described below. Mountain ranges (uplifts) border the Greater Green River Basin on all but the western edge, where the Thrust Belt borders it. The Greater Green River Basin is bounded on the south by the Uinta Mountains and Cherokee Ridge; on the southeast, east, and northeast by the Sierra Madre, Rawlins uplift, Granite Mountains, and Wind River Range; and on the north by the Gros Ventre Range. Three major sedimentary basins are found within the Greater Green River Basin —the Green River, Washakie, and Great Divide basins. The Green River Basin occupies the western half of the Greater Green River Basin, and is separated from the Great Divide and Washakie basins in the east half of the Greater Green River Basin by the north-trending Rock Springs uplift. More specific details for each of these basins are described in their own separate sections. The Wamsutter arch, an eastward extension of the Rock Springs uplift, is a structural divide that separates the Washakie Basin from the Great Divide Basin.

The Greater Green River Basin is part of the Wyoming Basins geomorphic province; as one might expect, topographic relief within the Greater Green River Basin is much less than the surrounding mountains, with the lowest areas occupied by stream drainages and the higher areas by cuestas, mesas, and plateaus. Only a very small part (about 30 square miles) of the Green River Structural Basin falls within the Platte River drainage on the far western end of the watershed at the headwaters of the Sweetwater River. This upland area is overlain by undifferentiated Tertiary rocks.

4.13 Wind River Range (WSGS, 2013)

The Wind River Range is the largest and highest discrete mountain mass in Wyoming, containing most of the state's highest summit peaks, such as Gannett Peak (at 13,804 feet, the highest point in Wyoming), Fremont Peak (13,745 feet), and Wind River Peak (13,192 feet). Trending N 40° W from South Pass City on the south to Fish Lake Mountain on the north, the range is a major barrier between western and central Wyoming; it separates the Wind River Basin to the northeast from the Greater Green River Basin to the south and southwest. The northeast flank of the Wind River Range consists of a 96-mile-long, continuous band of Paleozoic sedimentary rocks exposed in a series of hogbacks and dip slopes that dip eastward into the Wind River Basin. The core of the range exposes an extensive area of some of the oldest Precambrian rocks in the state. The southwest flank of the range is characterized by an extensive thrust fault system, with Precambrian rocks thrust south and southwest onto relatively flat-lying Tertiary rocks in the Green River Basin. The fault system extends eastward where Precambrian rocks in the South Pass area were thrust over Tertiary rocks of the northern Great Divide Basin. A survey by the Consortium for Continental Reflection Profiling (COCORP) used reflection seismology across the southern Wind River Range along Wyoming State Highway 28 to gather new data on crustal structure. The data revealed that the thrust fault along the western boundary of the range dips to the east at an angle of 30° and extends to a depth of approximately 18.7 miles.

Glaciated peaks mark the high central region of the range; glaciers and permanent snowfields lie in the higher valley heads. U-shaped glaciated valleys issue from both the east and west sides of the Continental Divide, which forms the backbone of the range. On the west side of the range, a broad bench-like platform at about 9,400 feet above sea level is dotted by a myriad of glacial lakes. This high, relatively flat subsummit surface above timberline is dissected, as if by a biscuit cutter, by steep-sided glacial valleys. The range's highest peaks stand high above the subsummit surface. At the base of the mountain flanks, long, deep, moraine-

dammed lakes—such as Fremont and New Fork on the west side and Dinwoody and Bull lakes on the east side—occupy valleys where glacial ice once flowed down from the higher regions onto the basin floor.

The South Pass area at the south end of the Wind River Range hosts a sequence of Archean (more than 2.5 billion years old) supracrustal metamorphic rocks called a greenstone belt that contains the state's principal gold deposits as well as iron ore deposits. Besides being an important point along the Oregon Trail, South Pass was also the site of extensive lode and placer gold mining in the 19th century and of a surface iron ore mine and mill in the 20th century. The area remains attractive for gold prospectors and has a rich and well-preserved history.

4.14 Hartville Uplift (WSGS, 2013)

The Hartville Uplift (**Plate 1; Figures 4-1** and **4-17** through **4-20**) and is a structural arch that separates the Denver Basin from the Powder River Basin. The arch extends from the northeast end of the Laramie Range to the south end of the Black Hills. Precambrian, Paleozoic, and Mesozoic rocks were raised along the arch during the Laramide orogeny, but were covered by the blanket of Cenozoic sediments. Today, there is very little topography to suggest that this is a structurally uplifted region. However, south of Glendo, to the east, Permian and Pennsylvanian-aged limestones, sandstones, and red shales poke through the blanket of Cenozoic strata to form tree-covered hills along the crest of the Hartville arch. These Paleozoic strata are also exposed in a large interstate highway roadcut at the north end of the Glendo Reservoir.

4.15 Denver Basin (Belitz and Bredehoeft, 1988, WSGS, 2013)

The Denver Basin (**Figures 4-1** and **4-20**), also known as the Denver Julesburg basin is a large (350 miles by 150 miles) oval shaped asymmetrical Laramide structural basin located in southeastern Wyoming, eastern Colorado, and western Nebraska. In Wyoming, the Denver structural basin is bounded on the north by the Hartville Uplift and on the west by the Laramie Mountains (Figure 3-2); the Cenozoic through Paleozoic sedimentary strata reach a maximum thickness of 12,000 feet near Cheyenne. The surface rocks here are nearly horizontal strata of Late Tertiary age, which lie unconformably on Paleozoic and Mesozoic rocks downfolded into a large trough. The trough extends southward from Cheyenne to Colorado Springs, Colorado. The axis of the trough lies a few miles east of the mountain front (Plate 1, inset). The maximum structural relief between the deepest area of the basin and the highest area of associated uplift in the Laramie Mountains exceeds 17,000 feet. This is the difference between elevations in the deepest part of the structural basin at approximately 7,000 feet below sea level near Cheyenne and at Laramie Peak, which is 10,274 feet above sea level.

4.16 Geothermal resources (Heasler and Hinkley, 1984; Hinkley and Heasler, 1986) - Figure 4-21

The geothermal resources of the Platte River Basin are of the low-temperature hydrothermal type, occurring where groundwater exists at anomalously elevated temperatures (relative to the average geothermal gradient). These elevated occurrences are not typically found at a depth where they can be put to beneficial use. Hydrothermal resources of the Platte River Basin are primarily suited to local, small-scale projects that utilize low-temperature waters for space-heating, de-icing, and recreational/ therapeutic applications (e.g., Saratoga Hot Springs).

Generally, groundwater is heated as it flows downdip into a structural basin in accord with the local geothermal gradient resulting from heat flow from deep in the earth toward the land surface. Platte River Basin hydrothermal resources occur primarily where the heated groundwater rises to shallower depth under artesian hydraulic pressures at velocities that preclude dissipation of the heat acquired at depth. This requires vigorous upward flow through permeable up-folded strata or up faults, fracture systems, or wells. In general, the conditions that control hydrothermal resources occur only within the more productive Mesozoic and Paleozoic aquifers in the Platte River Basin. The locations of known and potential areas of

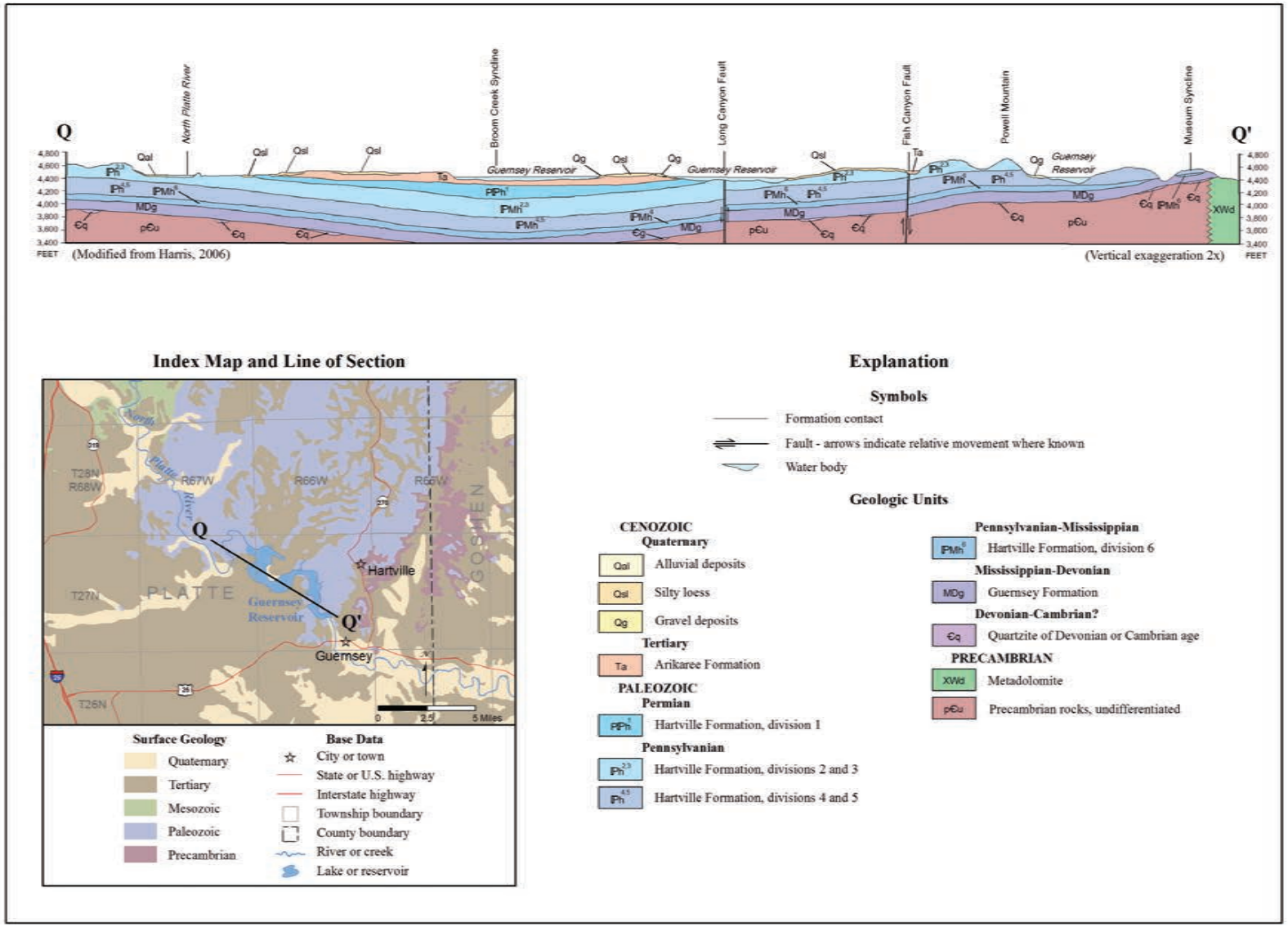


Figure 4-18. Geologic cross section Q-Q'.

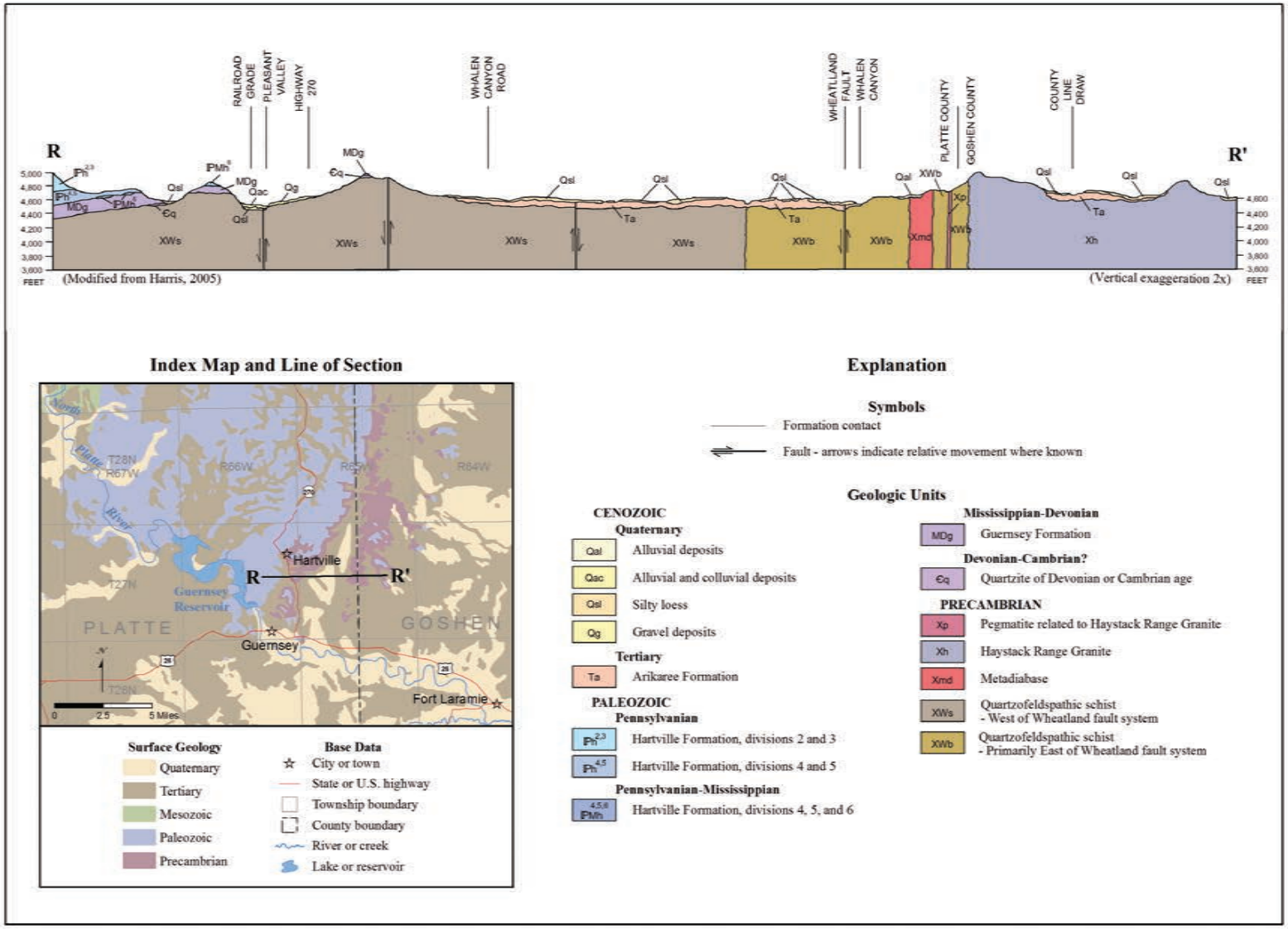
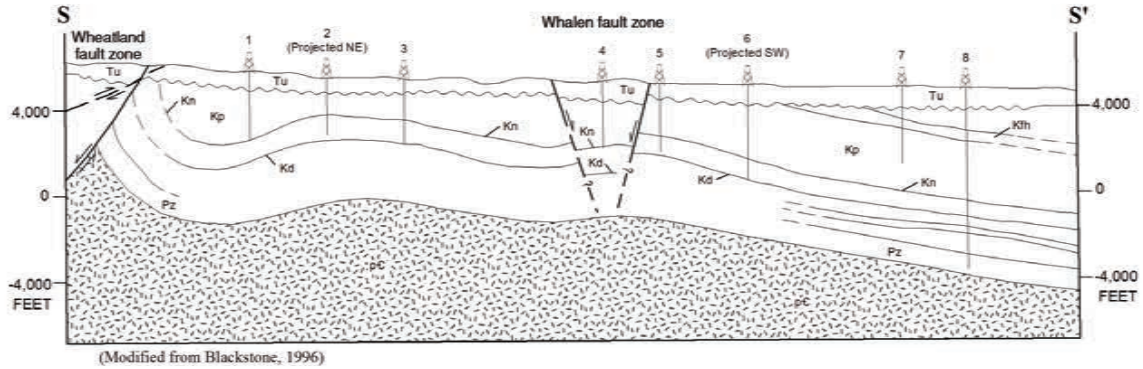
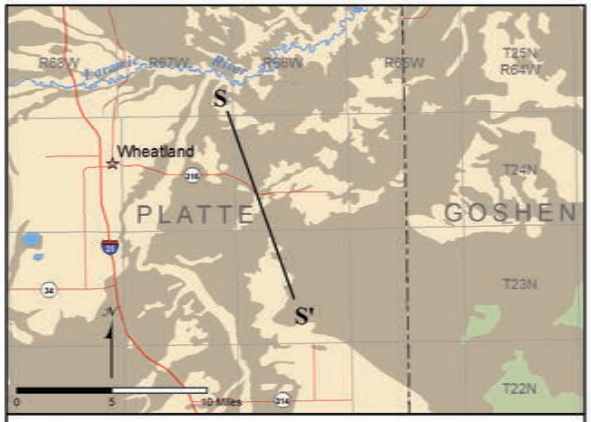


Figure 4-19. Geologic cross section R-R'.



(Modified from Blackstone, 1996)

Index Map and Line of Section



Surface Geology

- Quaternary
- Tertiary
- Mesozoic

Base Data

- City or town
- State or U.S. highway
- Interstate highway
- Township boundary
- County boundary
- River or creek
- Lake or reservoir

Explanation

Symbols

- Formation contact; symbol indicates formation top; dashed where inferred or poorly known
- Fault - dashed where inferred, queried where hypothetical or unknown; arrows indicate direction of relative movement
- Unconformity
- Well location and designation

Geologic Units

CENOZOIC

Tertiary

- Tu Tertiary rocks, undifferentiated

MESOZOIC

Cretaceous

- Kfh Fox Hills Sandstone
- Kp Pierre Shale
- Kn Niobrara Formation
- Kd "Dakota" sandstone (Cloverly Formation)

PALEOZOIC

- Pz Paleozoic rocks, undifferentiated

PRECAMBRIAN

- pC Precambrian rocks

Well Information

Well #	API #	Well Name	Location (Section-Township-Range)	Elevation (feet)	Depth (feet)	Bottom Formation	Spud Date
1	49-031-05009	PHIFER 1	18-24N-66W	4,631 KB	3,033	N/A	1956
2	49-031-20015	SHELL-FEDERAL 19-6	19-24N-66W	4,996 KB	2,740	Carlile Shale	1970
3	49-031-20031	SULLIVAN-JOHNSON 1	29-24N-66W	4,987 KB	3,208	Carlile Shale (Codell Sandstone)	1976
4	49-031-20004	GOVT 31-32	32-24N-66W	5,013 KB	3,080	Carlile Shale	1969
5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6	49-031-20022	JOHNSON 1	33-24N-66W	5,107 KB	4,520	Dakota	1975
7	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8	49-031-20038	BASS ASHENHURST FEE 16-31	16-23N-66W	5,142 GR	9,575	Precambrian	1982

GR = ground; KB = kelly bushing

Figure 4-20. Geologic cross section S-S'.

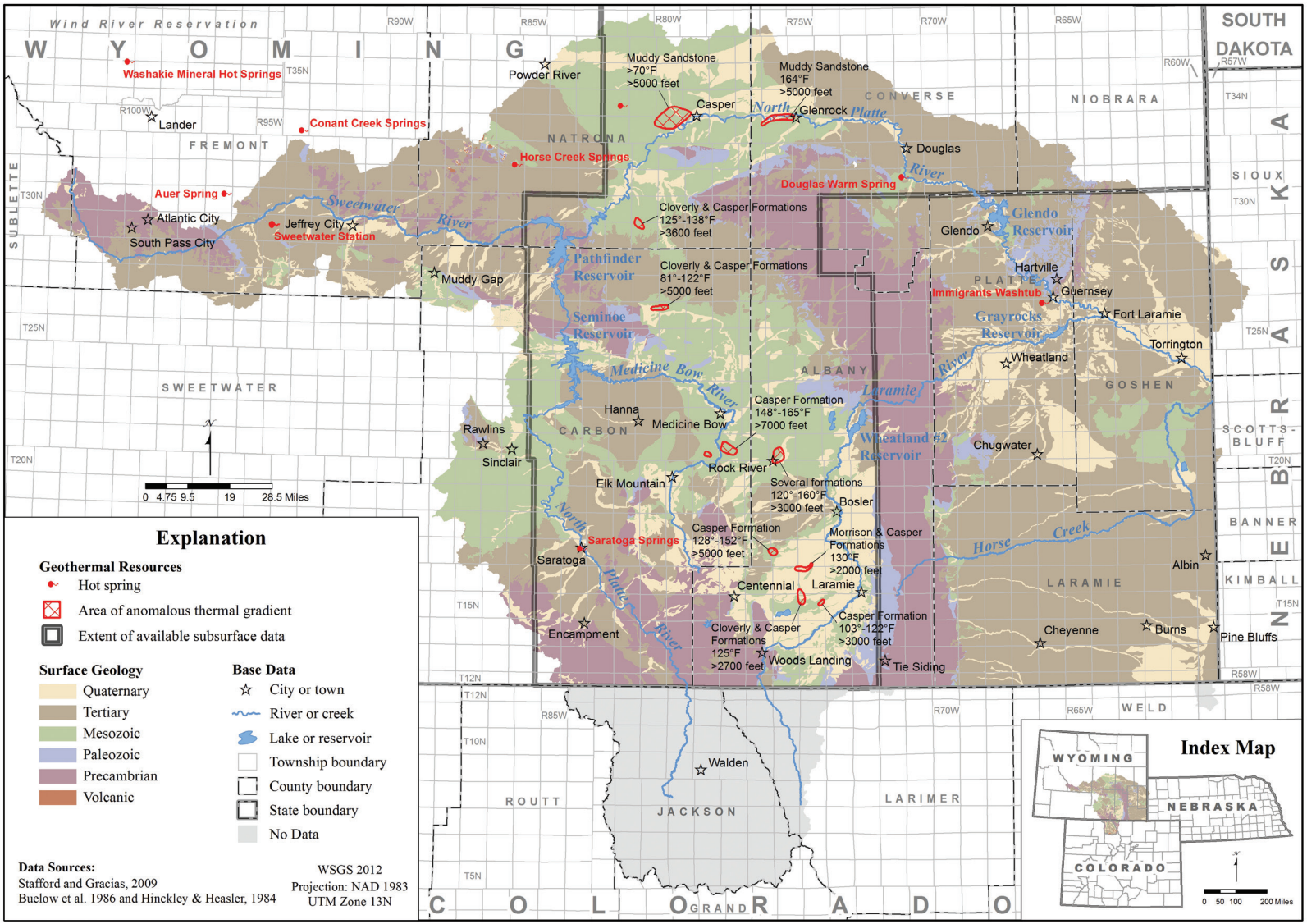


Figure 4-21. Geothermal resources, Platte River Basin.

hydrothermal resource development are shown on **Figure 4-21**.

4.17 Mineral resources

The development of mineral resources generally requires the use and proper disposal or surface discharge of groundwater and has a high potential to create avenues for groundwater contamination. **Figures 5-4, 5-7, 5-8, and 5-9** show the distribution of oil-and-gas operations and other active and historic mineral development locations within the Platte River Basin **(Section 5.7.2**). Even in areas without active mineral development, the presence of some naturally occurring minerals such as those that contain uranium, arsenic, and hydrocarbons, can, at significant concentrations, negatively impact groundwater quality. Some small communities in the northern part of the Platte River Basin have had to develop mitigation plans to address exceedances for naturally occurring radium, uranium and/or arsenic in their public water systems (WWC, 2011; Olsson Associates, 2008).

Significant quantities of oil and gas have been developed in the Platte River Basin primarily in the Casper Arch, High Plains and northern Great Divide Basin **(Figure 5-4)**. In the last few years, increased oil and gas exploration and production operations are focused on the Cretaceous Niobrara and Frontier Formations from Cheyenne north to Douglas. This trend has continued over the last year (June 1, 2012 to June 1, 2013) with over 140 Applications for Permit to Drill (APD) filed with the Wyoming Oil and Gas Conservation Commission (WOGCC) for wells in Converse County and 67 APDs approved for Laramie County. Again, most of these permits target the Niobrara Formation.

Substantial uranium and coal have been commercially developed in the Platte River Basin. Currently, there is no active coal mining in the Platte River Basin but uranium is mined by in-situ recovery extraction at the Smith Ranch-Highland operation 23 miles northwest of Douglas. Industrial minerals including sand, gravel, clay, limestone, dolomite, feldspar, shale, bentonite, and gypsum have been extensively mined within the Platte River Basin, and still are produced in many locales **(Figures 5-7, 5-8, and 5-9)**.

The Wyoming State Geologic Survey (WSGS) has evaluated many Wyoming sites for potential mineral development. These include precious metals (Hausel, 1989, 2002), gemstones (Hausel and Sutherland, 2000), base metals (Hausel, 1993, 1997), industrial minerals (Harris, 1992, 1996), decorative stones (Harris, 2003), coal (Jones and others, 2011), coal bed natural gas (WSGS, 2005) and oil and gas (Lynds, 2013). Although these reports and maps generally discuss groundwater, they do provide information on areas of future development that could create potential impacts on state groundwater resources. Mineral development in the Platte River Basin as a source of potential contamination to groundwater resources is further discussed in **Chapter 5.**

Chapter 5

Technical Concepts: Hydrogeology and Groundwater Quality

Paul Taucher, Timothy T. Bartos, Laura L. Hallberg, Melanie L. Clark, Karl Taboga, Jim Stafford, and Keith Clarey

This chapter discusses the technical concepts and terminology used in this study. Additional discussions and illustrations of the concepts commonly used in the study of groundwater resources can be found in U.S. Geological Survey (USGS) Water Supply Paper 2220 (Heath, 1983). *Hydrogeology* is the area of geology that studies the distribution and movement of groundwater through the bedrock and unconsolidated material (including soil) of the Earth's crust. In contrast, the term *geohydrology,* which is often used interchangeably, more properly describes a branch of engineering that studies subsurface fluids. Groundwater hydrology is deemed by the USGS to be the branch of hydrology concerned with the occurrence, movement, and chemistry of groundwater. The study of groundwater resources is an interdisciplinary field that requires extensive knowledge of geology along with an understanding of the basic principles of physics, chemistry, mathematics, biology, and engineering. Hydrogeologists must be able to understand the intricate physical and chemical interactions that occur between groundwater, host rock units, unconsolidated materials, minerals, and the surface environment.

Hydrogeology usually deals with groundwater that is accessible and can be directly used for the benefit of society. The shallowest groundwater resources (e.g., water-table and shallow confined aquifers) and their interactions with surface waters are of interest to geologists, water managers, soil scientists, agriculturalists, hydrologists, water law attorneys, civil engineers, and citizens who use these resources for their water supplies. Groundwater in deeper formations may be relatively inaccessible to the water well driller or, more often, of a quality that is too poor to use for potable water supplies. The hydrogeology of the deeper formations may still be important to mineral and petroleum resource geologists, geophysicists, and petroleum engineers. The suitability of groundwater for a particular beneficial use depends primarily on water quality. In this study, groundwater quality is evaluated relative to its suitability for domestic, irrigation, and livestock use, based on the Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA) and the Wyoming Department of Environmental Quality's (DEQ) class-of-use, water-quality standards **(Section 5.6.1; Chapter 7)**. Aquifer sensitivity, potential sources of groundwater contamination, and state and federal programs designed to characterize and protect groundwater quality in Wyoming are also discussed in this chapter.

5.1 Definitions and concepts

The movement of groundwater through and its chemical interaction with permeable earth materials can be complex. Highly variable geologic and hydraulic properties within an aquifer control flow, chemical composition, and availability. Fundamentally, groundwater is a slow-moving, viscous fluid that flows through interconnected voids in the host rock along pressure gradients (areas of high hydraulic pressure to areas of lower hydraulic pressure). The voids may consist of pores between individual mineral grains (intergranular space), fractures of varying sizes, faults, dissolution features such as tunnels and caves, vesicles in volcanic rocks or some combination of these. Voids range in size from microscopic to cavernous. Groundwater chemistry is determined by the mineral composition of the aquifer system and the residence time that the water is in contact with the earth materials through which it flows. Groundwater residence times can range from a few days, to hundreds of thousands of years.

5.1.1 Definitions

The following technical terms and concepts are either used in this study or have been provided to supplement the reader's understanding:

Geologic unit - a geologic formation, member, lens, tongue, bed, flow, other stratigraphic unit or group of rocks that have been correlated, named, and mapped by geologists based on lithological and geospatial continuity, and other properties. With the development of Geographic Information Systems (GIS) technology, Wyoming geologic units have been compiled into a database that can be modified, queried, and mapped based on specified geospatial, physical, and chemical criteria – such as the hydrologic characteristics described in this

study. An additional discussion on geologic units is provided in **Section 5.2**.

Lithostratigraphic unit – a mappable stratigraphic unit defined by lithologic uniformity and continuity. Lithostratigraphic and, to a lesser degree, other stratigraphic units are commonly characterized components of geologic units and are generally used in geologic mapping where allowed by the map scale. An additional discussion of lithostratigraphic units is provided in **Section 5.2**.

Hydrogeologic unit – one or more adjacent geologic units, or parts of geologic units (e.g., *lithostratigraphic units*), grouped according to their hydrologic characteristics, such as whether the designated unit functions as an *aquifer* or a *confining unit*.

Aquifer – a *geologic unit*, group of *geologic units*, or part of a *geologic unit* that contains adequate water-saturated and permeable materials to yield sufficient quantities of water to wells and springs (modified from Lohman and others, 1972) with "sufficient" generally defined in terms of ability to meet specified uses. Aquifers both store and convey groundwater. Aquifers are not defined on the basis of geologic unit boundaries, but on hydraulic characteristics, common recharge-discharge areas and mechanisms of the units that compose them.

Aquifer system – a heterogeneous body of saturated, interbedded geologic units with variable permeability that operates regionally as a major integrated water-bearing hydrogeologic unit. It comprises two or more smaller aquifers separated, at least locally, by strata with low permeability that impede groundwater movement between the component aquifers but do not preclude the regional hydraulic continuity of the system (modified from Poland and others, 1972). *Aquifers* and *aquifer systems* are generally anisotropic because of interbedded low-permeability strata (e.g., shale, claystone, mudstone, bentonite). Most *aquifer systems* also share the following characteristics:

- Regionally extensive.
- Common recharge and discharge areas and mechanisms.
- Similar hydraulic properties.
- Similar water-quality characteristics.
- Hydraulically isolated from younger and older aquifers/aquifer systems by thick and laterally extensive confining units.

Confining unit – a geologic unit, group of units, or part of a unit with very low hydraulic conductivity that impedes or precludes the movement of groundwater between the aquifers that it separates or between an aquifer and the ground surface. The hydraulic conductivity of a confining unit may range from essentially zero to a value substantially lower than that of an adjacent aquifer. *Confining units* are conventionally considered to be impermeable to groundwater flow, but most leak water at low to very low flow rates. Over large areas and extended periods of time, confining units can leak large quantities of water.

Confined aquifer – an aquifer overlain and underlain by confining units that limit groundwater flow into and out of the aquifer. Confined aquifers are completely saturated and under *artesian* pressure. An aquifer can be *semi-confined* if there is sufficient leakage through the adjacent confining unit(s).

Unconfined aquifer – the water-saturated part of a hydrogeologic unit containing groundwater under atmospheric pressure that will rise and fall relatively quickly in response to recharge (e.g., precipitation, irrigation) and changes in atmospheric pressure. Unconfined aquifers are generally saturated only in the lower part of the host hydrogeologic unit.

Alluvial aquifer – an aquifer composed of loose, unconsolidated sediments deposited by and along a streambed. Alluvial aquifers usually possess high degrees of hydrologic variability over short distances because the component clays, silts, sand, gravel, cobbles and boulders were unevenly deposited under shifting climatic and hydrologic conditions.

Bedrock aquifer – an aquifer that occurs within a consolidated rock unit. Groundwater is stored and transported within the pores of the solid rock, fractures, or solution cavities or any combination thereof.

Unconsolidated aquifer – a water bearing unit in loose, uncemented sediments such as sand, gravel, clays and silts.

Colluvium – Loose unconsolidated deposits placed primarily by gravity at the foot of a hillslope.

Colluvium includes deposits such as talus and cliff debris.

Perched groundwater or a *perched aquifer* – an unconfined lens of groundwater, generally limited in lateral extent, lying on top of a confining unit in a configuration similar to ponding. Perched groundwater generally occurs at shallower depths hydraulically unconnected to deeper, more laterally extensive unconfined or confined aquifers.

Potentiometric surface – a surface that represents the *total head* in an aquifer. Within a *confined aquifer*, it is a conceptual surface defined by the level to which water rises in wells completed in that aquifer. Within an *unconfined aquifer* it is a physical surface. *Potentiometric surface* has generally replaced the older terms *piezometric surface* and *water table*. A synonym is *groundwater surface*. The *potentiometric surface* is generally mapped by equal-elevation contours in feet above mean sea level (ft-msl).

Water table – the groundwater surface within an unconfined aquifer under atmospheric pressure. Although the *water table* is often considered the top of the zone of saturation, it is more correctly considered the surface where pore-water pressure equals atmospheric pressure; for while the *capillary fringe* above the *water table* is saturated, it is below atmospheric pressure. The term *water table* implies a flat, horizontal surface, but the actual surface is generally tilted or contoured like the land surface. In popular usage, the *water table* is the first occurrence of unconfined groundwater encountered below the ground surface and is generally equivalent to "*groundwater surface*" or "*potentiometric surface*".

Capillarity – the effect of surface tension and molecular attraction between liquids and solids that causes water within the vadose zone (above the water table) to be at less than atmospheric pressure. Groundwater in the *capillary fringe* immediately above the *water table* will be subject to an upward attraction.

Vadose zone – the depth interval between the ground surface and the water table that can include: 1) unsaturated soils, unsaturated bedrock, unconsolidated materials such as alluvium and colluvium, and weathered bedrock and, 2) the capillary fringe immediately above the water table.

Hydraulic gradient – the change in total head per unit distance measured in the direction of the steepest slope of the groundwater (potentiometric) surface. Hydraulic gradient has both direction and magnitude and is commonly expressed in feet of elevation change per foot of horizontal distance (ft/ft). The direction of maximum slope on the *potentiometric surface* (or normal to lines of equal elevation on the potentiometric surface), from high to low elevation, indicates the direction that groundwater will flow along permeable interconnected pathways within isotropic and homogeneous earth materials.

Total head – the height of a column of water above a datum due to a combination of elevation head and pressure head.

Static head or *static water level* – the level of water in a well when the well and surrounding wells are not being pumped and the *total head* in the aquifer is generally at equilibrium over a short time-frame. *Static head* or water level is commonly expressed in feet of elevation above mean sea level (ft-msl).

Drawdown – the lowering of the groundwater potentiometric surface (*head*) by discharge from an aquifer (pumping or natural discharge) expressed in feet of water level change. A rise in groundwater level is the opposite of drawdown.

Recharge – water that infiltrates at ground surface, penetrates the *vadose zone*, and reaches the *water table*.

Discharge – groundwater that flows from an aquifer. Discharge from an aquifer can occur naturally by flow into streams or lakes, by leakage into adjacent geologic units by flow from springs, by near-surface evapotranspiration, or artificially by pumping wells.

Evapotranspiration – the loss of water from the near-surface vadose zone to the atmosphere by the combined processes of evaporation (direct vapor-phase transfer from the soil) and transpiration (transfer through plant root systems and respiration).

Porosity (total) – the proportion of void or open-space volume (e.g., intergranular space, fractures, solution cavities, etc.) in a total volume of earth material (e.g., soil, unconsolidated deposit, bedrock), generally expressed as a percentage or decimal fraction.

Effective porosity – the proportion of the *total porosity* in a volume of earth material that is interconnected and allows the flow of groundwater. Water attached to solid surfaces within the interconnected *porosity* decreases effective porosity. Effective porosity is always less than total porosity.

Storage (total) – the total volume of groundwater contained within a volume of earth material – equal to saturated volume times porosity. *Storage* changes in response to changes in recharge and discharge.

Hydraulic conductivity – the capacity of earth materials to transmit groundwater, expressed as a measure of the amount of water that can flow through the interconnected open spaces of earth materials (gallons per day, per square foot - gpd/ft^2), or in terms of velocity (ft/day). *Hydraulic conductivity* is dependent on the physical characteristics of both the porous earth material and the fluid, and can be as variable as the lithologies that compose the Earth's crust. It can vary by direction; it is commonly much higher parallel to than across stratification.

Permeability – differs from *hydraulic conductivity* in that it depends only on the characteristics of the porous material. The dimensions of *permeability* are length squared (ft^2, cm^2, m^2, etc.). *Permeability* is the parameter preferred by the oil and gas industry where it is more practical for evaluating multi-phase fluid (oil, gas, water) flow.

Transmissivity – the rate at which groundwater moves through a unit width of the water-saturated portion of the aquifer, under a unit hydraulic gradient expressed in square feet per day (ft^2/day = ft/day <u>x ft</u>) or gallons per day, per foot (gpd/ft = gpd/ft^2 <u>x ft</u>). *Transmissivity* is equivalent to the hydraulic conductivity integrated over the thickness of an aquifer (<u>x ft</u> = aquifer thickness).

Specific capacity – the pumping discharge rate of a well divided by feet of drawdown of the water level in the well during pumping, commonly expressed in gallons per minute, per foot of drawdown (gpm/ft).

Specific yield – the drainable porosity of an unconfined aquifer, reported as a ratio of the volume of water that will drain under gravity, to the volume of saturated earth material. *Specific yield* is a dimensionless parameter that is commonly used to describe the proportion of aquifer material volume that provides water available for beneficial use. Compare *specific yield* to *porosity* and *effective porosity*: All three are dimensionless but multiplied by the volume of the saturated rock, porosity will equal total void space, effective porosity will return total groundwater volume, and specific yield will return the volume of available groundwater **(Section 5.1.4)**.

Storage coefficient – the volume of water released from or taken into storage per unit surface area of the aquifer, per unit change in head. Like *specific yield*, *storage coefficient* is a dimensionless parameter because dimensions in the numerator and denominator cancel. In an unconfined aquifer, the water released from storage is from gravity drainage and the *storage coefficient* is essentially equivalent to *specific yield*. In a confined aquifer, water released from storage, called *specific storage*, comes primarily from expansion of the water and compression of the aquifer as pressure is relieved during pumping. Because of the difference in mechanics of how water is released from storage, the storage coefficients of unconfined aquifers (0.1 to 0.3) are generally several orders of magnitude larger than those of confined aquifers (10^{-5} to 10^{-3}).

Specific retention – the ratio of the volume of water retained in the pores of an unconfined aquifer after gravity drainage to the total volume of earth material. *Specific retention* is a dimensionless parameter expressed as a percentage.

Well yield – the rate of groundwater discharged (pumped or flowing) from a well expressed in gallons per minute (gpm).

Artesian conditions – occur where the potentiometric surface of a confined aquifer is at a higher elevation than the top of the aquifer. Water in wells at these locations will rise above the top of the aquifer to the level of the potentiometric surface.

Gaining stream – a surface water stream or part of a stream, which receives discharges of groundwater from the underlying or adjacent hydrogeologic unit(s). Surface water flow attributed to groundwater is commonly referred to as *baseflow*.

Losing stream – a surface water stream, or part of a stream, which recharges the underlying

or adjacent hydrogeologic unit(s) resulting in decreased flow in the stream.

Total dissolved solids (TDS) – a measure of the total concentration of minerals dissolved in groundwater, generally expressed in either milligrams per liter (mg/l) or parts per million (ppm).

Geochemical water type – an expression of the dominant cations and anions dissolved in the groundwater.

5.1.2 Types of groundwater flow

Groundwater flow can be characterized as porous flow, conduit flow, fracture flow, or a combination of these three basic types:

- *Porous flow* occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone or unconsolidated deposit) or through intercrystalline pore spaces within igneous or metamorphic rocks. The size of the sediment grains or mineral crystals affects porous flow. Larger open pores between larger grains (or crystals) are generally more conducive to flow than smaller grains/pores due to reduced friction with the relatively lower surface area within the larger pores. In an aquifer with a wide range of grain sizes (poorly sorted), the fine-grained material fills in the larger pore spaces and reduces flow toward that of a fine-grained aquifer. Porous flow is also referred to as *primary porosity,* that is, the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the unfractured rock matrix.
- *Conduit flow* occurs through large, discrete open spaces (pipes, cavities, channels, caverns, other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite or salt. Conduits form by the dissolution of soluble minerals in bedrock or by subsurface sediment transport (piping) through unconsolidated or loosely consolidated material.
- *Fracture flow* occurs through interconnected partings in bedrock: fractures developed during structural deformation (folding, faulting), joints in rocks developed during expansion (with uplift and erosion) or compaction, cleats (in coal), or fractures resulting from physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation). Fractures occur either along or across existing bedding planes or other types of geologic contacts. The *porosity* of conduits and fractures is referred to as *secondary porosity,* although, frequently, conduits and fractures within a unit can transport water several times faster than the primary porosity in many aquifers.

5.1.3 Groundwater recharge, discharge, and flow

Groundwater systems at all scales, from local unconfined aquifers to entire groundwater basins, are defined by the physical factors that determine recharge, storage, and flow through the system to discharge areas. **Figure 5-1** is a cross section that illustrates some of the concepts discussed in this and other sections of this study.

5.1.3.1 Groundwater recharge

The accumulation of groundwater within an aquifer requires, first, a source of water and, in shallow aquifers, that source is ultimately precipitation. Initially, precipitation will infiltrate at the ground surface, percolate through the unsaturated, or vadose, zone and enter the water table. This process, alone, can take days to hundreds of years before the precipitation enters a receiving aquifer as "recharge." The path it travels from there, however, can be complicated further by moving between aquifers and confining units depending on the flowpaths within a particular system. Understanding the sources, amount and delivery timing of recharge is essential to effectively characterize any groundwater resource. Despite its importance, recharge is one of the most difficult

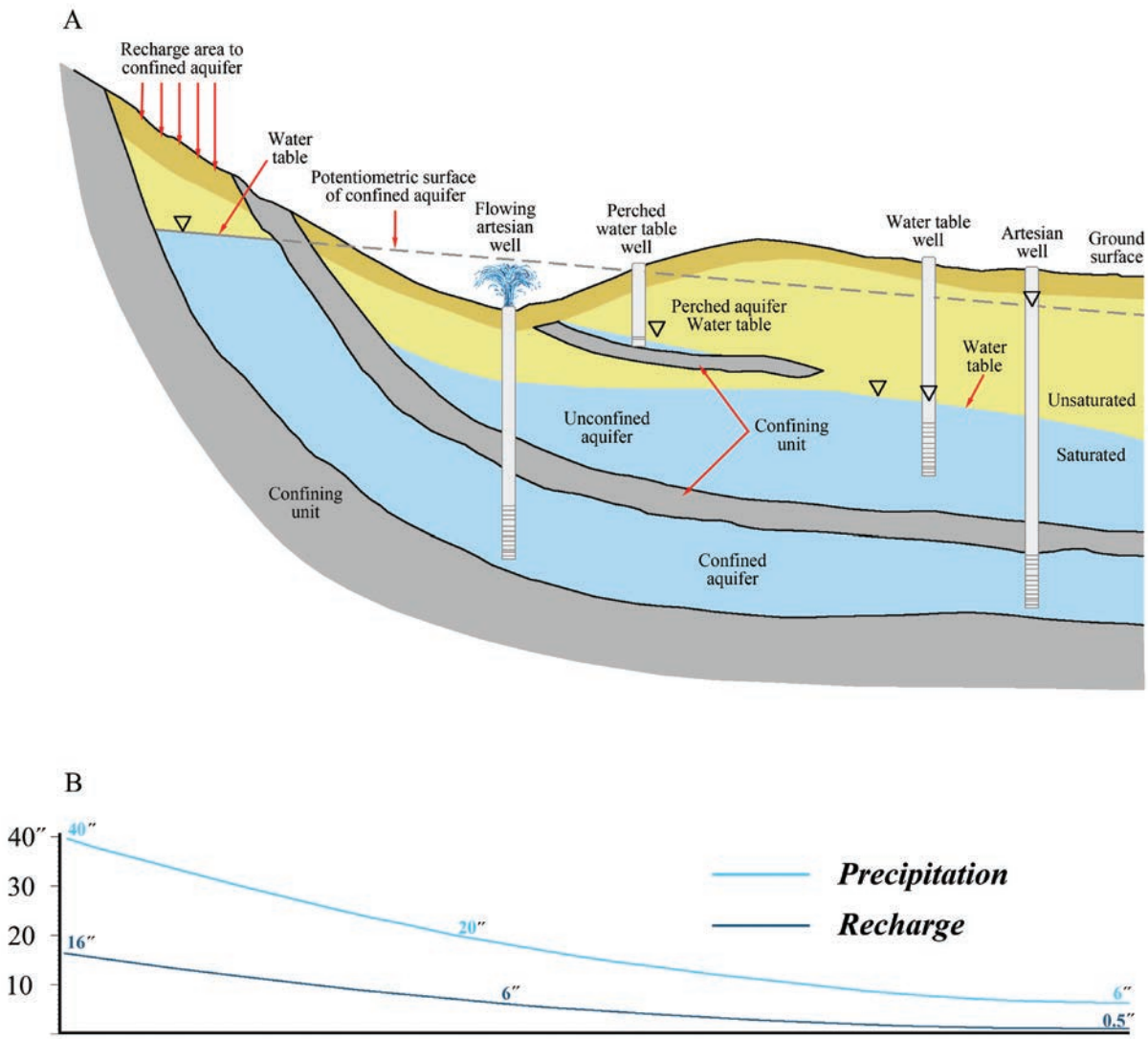


Figure 5-1. Conceptual cross-section of groundwater features that occur in a typical Rocky Mountain Laramide structural basin. Older hydrogeologic units outcrop and recharge at basin margins, dip steeply basinward, and become confined within short distances. Potentiometric surfaces for unconfined aquifers are marked with inverted triangles (water tables) and as a dashed line extending into the basin where the principal aquifer becomes confined. A perched aquifer has formed above a discontinuous confining unit. The figure shows water table wells completed in unconfined aquifers, and flowing and non-flowing artesian wells completed in the confined aquifer. B. Idealized Platte River Basin/recharge profile, in inches, basin margin to basin center. Adapted from WWC Engineering and others, 2007.

parameters to accurately quantify. Recharge cannot be measured directly, but must be estimated from other measurements and determinations.

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (**Figure 5-1**) and serve as significant sources of recharge. Consequently, the most important recharge areas in Wyoming are hydraulically connected with sources of mountain precipitation. The recharge that infiltrates alluvial materials and bedrock outcrops that border the mountain ranges (mountain front recharge), and the thick alluvial deposits underlying stream channels that receive a large proportion of their flows from mountain discharges is especially valuable. Recharge storage in Wyoming builds as snowpack accumulation during late fall, winter, and early spring when seasonal precipitation is

higher and cool daily mean temperatures prevent melting. Recharge rates are highest in late spring and the earliest part of summer during and following snowmelt when vegetation is still in a quasi-dormant state, rates of evapotranspiration are relatively low, and soils have newly thawed. The melting snowpack maximizes contact with the ground surface and enhances the duration and rate of infiltration.

Conversely, the environmental conditions that exist in the semi-arid basins limit the amount and delivery of recharge. There, evapotranspiration rates frequently exceed the low rates of precipitation. During most years, basin recharge events are limited to infrequent rainfalls, usually in the form of high intensity thunderstorms and springtime melting of the relatively thin prairie snowpack. The reduced permeabilities of basin soils, lower permeability and less efficient recharge across horizontal stratigraphic units, and the high efficiency with which semi-arid types of vegetation can utilize sporadic precipitation further restrict the amount of water available for recharge.

During a precipitation event, some of the moisture is intercepted by vegetation before it reaches the ground surface. This water, called *canopy storage*, is retained briefly and will later be lost to evaporation or fall to the ground. Precipitation that reaches the surface will infiltrate into the ground if the infiltration capacity of the soil has not been exceeded. Initially, infiltrating water will replace any depletion in soil moisture, and then the remaining infiltrating water will percolate downward under the force of gravity through the unsaturated zone to the water table. The hydraulic characteristics and antecedent moisture conditions of the unsaturated zone affect the amount and speed of the infiltrating water that reaches the water table. If the infiltration capacity of the soil is exceeded, overland flow occurs and flows in nearby streams may be augmented. In that case, some of the overland flow may infiltrate the streambed and enter the receiving aquifer as recharge, downstream from the site of precipitation. A general assumption is that approximately 10 percent of precipitation recharges groundwater. The description given above is a general simplification of the infiltration process. It should be understood that infiltration rates can vary widely and are affected by multiple factors:

- Depth, composition, and hydraulic properties of the surficial materials (soil, bedrock and paving).
- Depth and degree of bedrock weathering.
- Antecedent soil moisture conditions; was the soil dry, moist or wet before the event.
- Type, abundance, and density of vegetation.
- Extent, density and proximity of root zones.
- Type, rate, and duration of precipitation.
- Evapotranspiration (ET) rates.
- Slope and aspect of the ground surface.
- Aperture, depth, interconnection, orientation, density and exposure of fractures in bedrock.
- Large natural (caves, animal burrows) and man-made (mines, pits) openings.
- Geospatial distribution, capacity and permeability of surface depressions.
- Opportunity for recharge from surface waters.
- Local land use (irrigation, soil stripping, paved areas).

Recharge can also occur by leakage from and through confining units into a receiving aquifer if permeability exists between the two units and the hydraulic gradient allows flow into the receiving aquifer. While the rate of leakage from confining units is by definition very slow, the volume of leakage may be quite substantial over time if the geospatial area of contact between the aquifer and confining unit is large.

Artificial recharge from surface water diversion projects such as reservoirs, irrigation canals, and unlined pits, injection wells, and flow between aquifers in poorly completed wells may be significant in local areas of the Platte River Basin. The extent of artificial recharge is difficult to evaluate on a regional basis, but might be determined for a local area.

While several methods have been described for estimating recharge (Healy and Scanlon, 2010), direct measurement of recharge is problematic due to the high degree of geospatial and temporal variability of precipitation and the numerous factors that affect infiltration.

For this study, data from a statewide quantitative evaluation of recharge prepared by the Spatial Data

and Visualization Center (SDVC) for the *Wyoming Ground Water Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998) was modified to estimate recharge over the Platte River Basin **(Chapter 6)**. The original SDVC average annual recharge data is based on published percolation percentages for documented soil/vegetation combinations and average annual precipitation from 1961 through 1990 from the PRISM Climate Group. The SDVC calculated average annual recharge using the percentages; the SDVC general approach included:

- Compiling a map of soil-management-unit boundaries with assigned recharge fraction values (R/P = Average annual recharge / Average annual precipitation), as percentages of precipitation that reaches the uppermost aquifer in a given environment.
- Combining similar geologic units.
- Overlaying the average annual precipitation map and multiplying recharge fraction by precipitation to calculate average annual recharge.

Hamerlinck and Arneson (1998) observed several general relationships in the scientific literature on recharge:

- Recharge fraction (R/P) increases as the depth to the water table decreases.
- Recharge fraction increases as precipitation increases.
- Recharge fraction increases as the sand content of the soil increases.
- Recharge fraction is higher in an above-average precipitation year and lower when precipitation is below average.
- Seasonal patterns and the timing of major events like spring snowmelt alter the fraction of mean annual precipitation that recharges groundwater.

Hamerlinck and Arneson also provide additional discussion on the methods they used to evaluate aquifer vulnerability and quantify recharge. A discussion of the various other methods for determining recharge rates is beyond the scope of this study.

In contrast to the 1961–1990 precipitation data used by Hamerlinck and Arneson (1998), this study uses updated precipitation data (PRISM Climate Group, 2012) for the 30 year period of record from 1981 through 2010. The average annual volumes of precipitation for the two periods of record are not significantly different. The PRISM data indicates that annual rainfall in the Platte River Basin averaged 19,935,860 acre-ft from 1961-1990 and 19,677,577 acre-ft from 1981-2010. It should be noted that the PRISM analyses that generated the two datasets used different cell sizes and the higher resolution (smaller cell size) of the 1981-2010 data more closely fits the boundary used for the Platte River Basin in this study. **Table 5-1** contains summary statistics for the two periods of record.

5.1.3.2 Groundwater discharge

Natural discharges of groundwater occur in many ways. In Wyoming basins, the most common modes of discharge include leakage between geologic units, flow from springs, subsurface seepage into streams (baseflow), wetlands, lakes, and other surface waters (especially within thick alluvial deposits, and direct evaporation where the water table is shallow enough that capillarity or plant transpiration brings groundwater to the surface (evapotranspiration). Like recharge, the magnitude of natural discharge is difficult to determine, especially on a basin-wide basis. Some forms of discharge such as spring flows are readily measured. Others are difficult to quantify because they are concealed (leakage between geologic units or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). These discharges cannot be measured directly but must be estimated

Table 5-1 – Average annual precipitation statistics for the Platte River Basin for two 30 year periods of record, 1961–1990 and 198 – 2010 (PRISM Climate Group, 2012).

30 Year Period of Record	1961 - 1990	1981 - 2010
Average annual volume (acre-feet)	19,935,860	19,677,577
Calculated surface area (acres)	15,446,042	15,417,209
Weighted average annual precipitation (inches)	15.49	15.32

from other measurements and calculations; for example, using a mass balance (water balance) model if enough information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available **(Chapter 8)**.

In addition to withdrawals from wells, artificial avenues of groundwater discharge include seepage into mines and other excavations, discharges into irrigation and drainage canals; and flow between aquifers in poorly completed wells. In some areas of the Platte River Basin, drainage tiles that discharge shallow groundwater directly to surface waters are installed in irrigated lands to lower the water table and prevent waterlogging and salt deposition. Groundwater withdrawals for beneficial use are estimated in the previous Water Plan (Trihydro Corporation and others, 2006a) and are discussed in **Chapter 8**.

Groundwater discharge, buffered by the storage function of an aquifer, is generally a more efficient process than recharge and occurs over smaller areas. While recharge occurs intermittently by percolation through unsaturated materials, discharge is a more continuous process that occurs under more efficient saturated flow conditions. Under natural conditions, where there is no extraction of groundwater, recharge and discharge will reach a state of dynamic equilibrium over a time period that depends on precipitation, hydrogeologic characteristics, aquifer size, and the variability of the particular hydrologic inputs and outputs within the groundwater basin in question. Reasonable estimates of both recharge and discharge are necessary to evaluate safe/sustainable yield.

5.1.3.3 Groundwater flow

Gravity drives groundwater flow. After water enters an aquifer in a recharge area it flows under saturated conditions to discharge areas controlled by the hydrogeologic characteristics of the aquifer. The rate of groundwater flow (as volume per unit of time) is determined by the hydraulic conductivity (the velocity with which water can move through the pore space), the cross-sectional area, and the gradient that prevail along the flow path. The time it takes for water to circulate through an aquifer can range from a few days in a shallow, permeable aquifer, to thousands of years in the deeper aquifers of a groundwater basin. The arrangement of aquifers and confining units that function as reservoirs and the plumbing system constitutes the framework of the groundwater flow system within a structural groundwater basin.

Although groundwater flow is driven by gravity, water does not always flow downward, but from areas of higher hydraulic pressure to areas of lower hydraulic pressure. In the deeper subsurface, groundwater can flow from a lower to a higher elevation, as observed at artesian wells and some springs that discharge groundwater from deep aquifers (**Figure 5-1**). Groundwater will flow in the directions indicated on potentiometric surface maps if permeable pathways exist; however, flow along preferential pathways (e.g., fractures and faults) can depart from the direction of maximum gradient. Hydraulic gradients are commonly steep in low-permeability geologic units where there is substantial resistance (friction) to flow and low-angle to nearly horizontal within high-permeability units where friction is low. The slope of the potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where there is no resistance to flow in any direction and the gradient due to gravity is flat.

Groundwater flow rates through aquifers and confining units range from very high to very low, to essentially no-flow. The flow rate through the pores of a highly permeable aquifer of well-sorted, gravel or through the large open conduits in a carbonate aquifer may be several feet per second (fps), whereas the flow rate within a clay-rich unit with very low, to essentially no permeability may be less than a few inches every 10,000 years. Hydraulic conductivity varies over 13 orders of magnitude in differing types of hydrogeologic units. Folding, fracturing, and faulting modify the permeability and other hydraulic properties of both aquifers and confining units, generally increasing permeability and decreasing the capacity of confining units to function as barriers to groundwater flow.

Groundwater occurs under unconfined (water table) conditions in unconsolidated deposits and bedrock formation outcrop areas throughout the Platte River Basin. In shallow, unconfined aquifers, recharge, flow, and discharge are predominantly

controlled by topography, vegetation and stream drainage patterns. The water table of an unconfined aquifer is recharged by precipitation and generally reflects the overlying topography especially in areas of high relief. Groundwater from unconfined aquifers can discharge to the surface at springs where the elevation of the water table is greater than the surface elevation. Complex interactions can occur among bedrock aquifers, unconsolidated aquifers, and surface waters, especially along drainages lined with alluvial deposits. The discharge of groundwater to surface drainages contributes to base flow and in some cases constitutes all base flow.

Recharge of the deeper aquifers in the Platte River Basin occurs primarily in areas where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeters of the structural basins. These aquifers are unconfined at the outcrop areas, but as groundwater flows downdip from the recharge areas into the structural basins, it becomes confined by overlying low-permeability strata such as shale and claystone bounding the more permeable aquifers of sandstone, coal, fractured limestone and dolomite. Some recharge to deeper aquifers occurs as leakage from adjacent, usually underlying, hydrogeologic units. Groundwater discharges from confined aquifers to the surface can occur under several conditions. Contact springs discharge where recharge is rejected from fully saturated aquifers into headwater streams at the point where a streambed intersects the surface between a confining unit and an underlying aquifer. Springs also form where joints, fractures, or faults through a confining unit permit flow from an underlying aquifer to reach ground surface. Artesian wells will flow when the pressure head in the confined aquifer is higher than atmospheric pressure at land surface.

Confined groundwater flow within the deeper bedrock formations of the structural basins of the Platte River Basin is commonly controlled by structure and stratigraphy. Major aquifers and aquifer systems in the Platte River Basin occur predominantly within interstratified sequences of high- and low-permeability sedimentary strata. The aquifers are commonly heterogeneous and anisotropic on both local and regional scales. Deeper groundwater flow in the Platte River Basin is predominantly through permeable formations down-gradient (from higher to lower hydraulic pressure) and generally down-dip toward the axes of the structural basins. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage and safe / sustainable / optimal yield

In addition to functioning as the plumbing (conveyance) system for groundwater flow, the saturated geologic units that compose the framework of the Platte River Basin groundwater basins also function as reservoirs that store enormous volumes of groundwater. Understanding how groundwater is stored and how to utilize the resource without depleting it (safe/sustainable yield) is of concern in most development projects. An exception is coalbed natural gas (CBNG) development, where lowering hydraulic pressure in coalbed aquifers is the purpose of groundwater extraction.

An important aspect of groundwater resource assessments, on either a local or regional scale, is the evaluation of both the total volume of groundwater present in an aquifer and the fraction of that volume that can be accessed, developed at an acceptable cost and put to beneficial use. Technical, financial, and cultural factors determine what fraction of the total volume of groundwater stored within a particular aquifer can be considered an available resource. That only part of the groundwater contained within an aquifer will be producible, and part will be retained within the aquifer fundamentally affects available volume. Development costs and water quality requirements are also primary factors that determine what part of the groundwater contained within an aquifer will be producible. The depth to the resource and other physical, cultural, legal, and institutional constraints of the project under consideration may limit accessibility and preclude the development of a particular groundwater resource due to associated costs or technical limitations. Groundwater must be of suitable quality to satisfy the requirements for its intended use. Groundwater quality is addressed in **Section 5.6 and Chapter 7**.

The amount of water that an aquifer will yield to natural drainage or to pumping is determined by its hydraulic properties, which are directly or indirectly dependent on an aquifer's *effective porosity* **(Section 5.1.1)**. Two of the most important hydraulic properties with respect to the sustainable development of groundwater resources are *specific yield* and *storage coefficient*.

Specific yield applies only to unconfined aquifers; it is the fraction of water that a saturated unit volume of rock will yield by gravity drainage. *Specific yield* is expressed as a percent (or decimal fraction) of the unit volume. In an unconfined aquifer, specific yield is essentially the same as effective porosity. *Specific retention* is the volume of water that remains in the unit volume of rock after drainage, in isolated pores and attached to the aquifer matrix by molecular attraction and surface tension (capillarity). The sum of specific yield and specific retention equals *total porosity*. Because capillarity is higher in fine-grained materials (with smaller pore size and proportionately greater pore-surface area), it follows that finer-grained aquifers in general have higher specific retentions than coarser-grained aquifers even though finer-grained materials may have higher total porosity than coarser-grained materials. For example, a larger fraction of the total water would be retained after drainage in a cubic foot of fine sand, than in a cubic foot of river cobbles. Highly productive unconfined aquifers are characterized by high specific yields.

The concept of *storage coefficient* can be applied to either an unconfined or a confined aquifer. The storage coefficient is the amount of water that a unit volume of an aquifer will release from (or take into) storage per unit change in hydraulic head, expressed as percentage or decimal fraction. The mechanisms of releasing groundwater from unconfined and confined aquifers are very different. In an unconfined aquifer, water is simply drained by gravity and hydraulic head is lowered. In a confined aquifer, water released from storage comes from the expansion of groundwater and the compression of the rock matrix as water pressure is reduced by pumping or artesian discharge. This is called the *specific storage*. Because the volume of water that is produced due to these elastic properties (*specific storage*) is negligible in an unconfined aquifer, the storage coefficient in an unconfined aquifer is essentially equal to specific yield. Conversely, specific yield cannot be determined for a confined aquifer unless the water level (hydraulic head) is reduced to the point that the aquifer becomes unconfined, at which point the storage coefficient is essentially equal to the specific yield. Pumping an aquifer to the extent that recharge is inadequate to maintain confined conditions is referred to as "mining the aquifer."

The storage function of an aquifer operates as a buffer between recharge and discharge, allowing relatively constant production of groundwater during periods of variable recharge. Enormous volumes of water can be released from storage in a geospatially large aquifer from relatively small persistent declines in hydraulic head, allowing continual withdrawal through periods of deficient recharge. Large declines in hydraulic head, however, can induce recharge by turning gaining streams into losing streams or drying up spring flows. Because of the difference in how water is released from storage, *specific yields* in unconfined aquifers are generally orders of magnitude larger than the *specific storage* of confined aquifers. Thus, unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than do confined aquifers. Unconfined aquifers are therefore generally more attractive prospects for development. Properly managed, groundwater is one of society's most important renewable resources; however, over-pumping can result in a long-term and perhaps irreversible loss of sustainability through compression of the aquifer material.

The terms "safe yield" and "sustainable yield" have been used to describe the rate of groundwater production that can be sustained without causing an unacceptable level of depletion of storage volume or other negative effects, such as degradation of groundwater quality or depletion of surface water flows. A safe/sustainable yield estimate predicts the response of an aquifer to long-term withdrawals and recharge inflows. In reality, though, such projections are complicated by the fact that recharge is not delivered immediately. Aquifer response times can range from days to hundreds of years. For example, in the High Plains aquifer, Sophocleous (2005) estimated that

an increase in soil moisture below the deep root level resulting from raised annual precipitation levels may not be delivered to the saturated zone as increased recharge for 144 years. Therefore, the changes in storage, currently observed, commonly reflect present day withdrawals and precipitation levels from decades past. In such cases, water managers must be careful to avoid evaluating current aquifer storage volumes relative to recent precipitation rates given the long lag times of some aquifers and the cyclic nature of drought in the semi-arid west.

The concept of safe/sustainable yield has been applied over a wide range of scale, from individual wells to entire structural or drainage basins. Meinzer (1923, p. 55) defined the *safe yield* of an aquifer as "*. . . the rate at which ground water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible.*" However, it is now recognized that ownership, legal, financial and environmental issues, the potential for aquifer damage, and interference with the development of other resources must also be considered in evaluating "safe yield" for groundwater development. Given these considerations, the definition given by Fetter (2001) is currently more applicable, *"The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head by pumping."* Because groundwater has value only to the extent that it can be put to a beneficial use, perhaps "optimal yield" in the context of a range of options from deliberately depleting (mining) an aquifer (e.g., for CBNG development) to total conservation (e.g., for wetlands maintenance) may be a more useful concept than safe/sustainable yield. In any case, end-users and resource managers must understand that any "yield" number will be dynamic and vary with time in response to changing cultural considerations, and environmental conditions such as extended drought.

Regional groundwater resources are generally evaluated within the conceptual model of a groundwater basin. Within this three-dimensional framework, the feasibility and sustainability of groundwater development can be analyzed by a conservation-of-mass approach variously referred to as a **water balance**, hydrologic budget, water budget, or hydrologic equation. The fundamental expression for this type of analysis as applied to groundwater resources is:

Recharge – Discharge = Change in Storage
(measured over the same time period)

Precipitation is the ultimate source of groundwater recharge, and both estimated precipitation and recharge have been mapped over the entire Platte River Basin (**Figures 3-3 and 5-2**). Discharge is more difficult to estimate. Considered on the scale of a groundwater basin, discharge is essentially composed of natural discharge to surface water that flows out of the basin, subsurface groundwater flows out of the basin in alluvial sediments underlying streams, evapotranspiration, and groundwater withdrawals that are not returned to the groundwater system. Long term changes in storage can be neutral (dynamic equilibrium), positive or negative. However, changes in aquifer storage must be evaluated for time periods that consider the response time of the target aquifer. This approach can be applied over a wide range of data density, with analyses often based on rough estimates of the variables in the water balance equation, especially for basin-wide studies. Accordingly, the results reflect the variability of the estimates.

In the best case for groundwater development within an aquifer with current withdrawals, groundwater in storage would be increasing, with long-term average recharge adequate to prevent depletion of storage. It is tempting and sometimes attempted, to estimate safe/sustainable yield as the amount of groundwater withdrawal that does not exceed average recharge. It is well known that this is not correct; however, the amount of water that can be withdrawn from a typical groundwater basin is fundamentally controlled by recharge, especially as withdrawal approaches or exceeds recharge. The water-balance equation shows that in addition to withdrawal, natural discharge also determines the amount of groundwater that is maintained in storage. The amount of water that can be

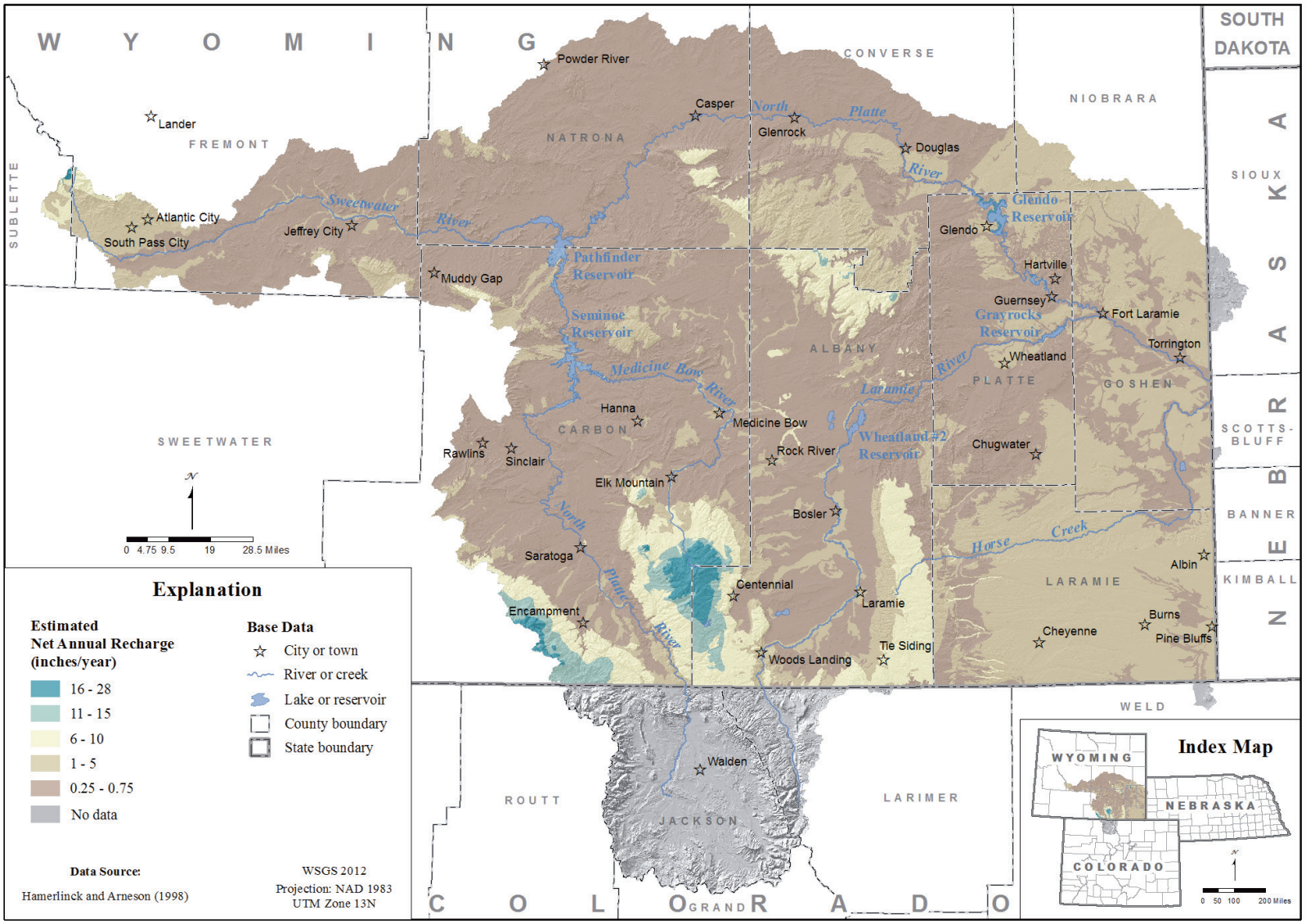


Figure 5-2. Estimated net annual aquifer recharge, Platte River Basin, Wyoming.

withdrawn from an aquifer or aquifer system that would not impact storage to an unacceptable degree might be defined as optimal yield – the portion of total discharge that is not already being utilized (existing withdrawals, baseflow to surface streams, etc.). Optimal development of all water resources within a basin would ultimately consider the conjunctive use of surface water and groundwater, especially where these resources are physically interconnected.

The unused or "available" part of natural discharge included in total discharge in the water balance equation is difficult to determine. Data for total discharge and its components, natural discharge and groundwater withdrawals, are generally not adequate to perform an evaluation using the water balance approach. The approach used in this study for evaluating groundwater resources **(Chapter 6)** is to consider average annual recharge over the areas of the aquifers exposed within Platte River Basin, restrained by a best estimate of total discharge. Average annual recharge rates for the Platte River Basin estimated by the SDVC (Hamerlinck and Arneson, 1998), are presented in **Figure 5-2**. Based on the SDVC evaluation, annual recharge to specific groups of aquifers is estimated and discussed in **Section 6.2**. A water balance for the Platte River Basin was prepared for this study **(Chapter 8)** using information provided in the previous Platte River Basin Water Plan (Trihydro Corporation and others, 2006a) and additional information developed by the WSGS. The aquifer-specific recharge estimates contained in **Chapter 6** of this study were integrated into the water balance to estimate a range of "sustainable" groundwater resources in the Platte River Basin **(Section 8 and Chapter 9)**. Still, the estimates for natural and total discharge volumes are highly uncertain and may never be adequately resolved.

5.2 Map/rock units: geologic units, stratigraphic units, hydrogeologic units

The geologic framework for the Available Groundwater Determination, Technical Memorandum for the Platte River Basin is the assemblage of rocks and other geologic elements that compose the groundwater basins, their hydrologic properties, and the stratigraphic and structural interrelationships that affect recharge, storage, and groundwater flow. *Geologic units* and *rock units* are distinct *mappable units* (described in **Appendix A** and discussed further in **Chapter 7**) that have been defined and described in the geologic nomenclature. They are classified in descending order of magnitude as supergroups, groups, formations, members, beds, tongues, and flows, and other *units* familiar to geologists.

The 2005 North American Stratigraphic Code establishes the basis for the definition, classification, and naming (nomenclature) of distinct and mappable bodies of rock. These bodies are referred to as *geologic units* and *rock units*. While the code does not clearly distinguish between the two, *rock units* are commonly considered equivalent to *lithostratigraphic units*, defined by mappability, stratigraphic position and lithologic consistency. *Geologic units* are distinguished over a wider range of properties such as lithology, petrography, and paleontology and can include lithostratigraphic (lithodemic for non-layered intrusive and metamorphic rocks), biostratigraphic, chronostratigraphic, geochronologic, and other less familiar stratigraphic units. *Stratigraphic units* are generally layered or tabular and established on the basis of any or several of the properties that distinguish them from adjacent *geologic units*.

The USGS Geologic Map of Wyoming (Love and Christiansen, 1985) provides the most comprehensive and up-to-date map of surface geology readily available and relevant for this study. The map delineates the surface outcrops of distinguishable bodies of "*rocks*" as "*map units.*" The Explanation sheet (Sheet II) of the Geologic Map of Wyoming describes where certain *map/rock units* that consist of one or more *stratigraphic units* have been combined on the map because of cartographic limitations. The explanation also describes the chronologic and geographic correlations between stratigraphic and map units, and the geographic and chronological distribution of both the map units and their component stratigraphic units. The WSGS "Stratigraphic Chart Showing Phanerozoic Nomenclature for the State of Wyoming" (Love and others, 1993) correlates the *stratigraphic units* shown on the 1985

map explanation developed from the individual 1° x 2° (1:250,000 scale) geologic quadrangle maps covering the state, and includes revisions subsequent to the 1985 map. Conceptually, because the *map/rock units* of the Geologic Map of Wyoming may consist of more strictly defined stratigraphic units (primarily *lithostratigraphic units*), they are considered to be *geologic units*. The USGS and the WSGS compiled the map/rock units in the 1985 Geologic Map of Wyoming into a digital database of *GIS geologic units* which was used in the development of **Plate 1** (surface geology), **Plate 2** (surface hydrogeology) and the hydrostratigraphic charts contained in **Plates J, K, M, S, T, U** and **Figure 7.2**.

The Platte River Basin *GIS geologic units* mapped on **Plate 1** are described in **Appendix A.** Throughout this study, bodies of rock are described in terms of *rock (lithostratigraphic) units* where the more restrictive distinction is applicable (primarily in **Chapter 7**) and as geologic units where a more inclusive definition is appropriate.

Plate 2 maps the exposures of the *hydrogeologic units* in the Platte River Basin. Hydrogeologic units can be composed of multiple, or portions of geologic and/or rock units. The units that compose an aquifer or aquifer system in one area may be considered differently in another area where the same units have different hydrologic properties or are composed of different geologic units. The hydraulic, physical, and hydrogeochemical characteristics of individual hydrogeologic units (aquifers and confining units) established on the hydrostratigraphic charts are discussed in detail in **Chapter 7** regarding their component geologic or lithostratigraphic units.

Plates J, K, M, S, T, U and **Figure 7.2** also provide hydrostratigraphic information from previous studies so that informed readers can track the historical development of the basin's hydrostratigraphy. The hydrostratigraphic charts are based on *stratigraphic units*, several of which are not distinguished within the *GIS geologic units* used to develop **Plate 2**. In addition, *GIS geologic units* used to map specific *hydrogeologic units* comprise different *stratigraphic units* in different areas in the Platte River Basin. This limitation precluded designating some GIS units as a specific **Plate 2** aquifer or confining unit. In cases where specific designations could not be made (some Mesozoic and Paleozoic units), the hydrogeologic units on **Plate 2** are categorized as *undifferentiated*.

Most geologic maps are now developed using computers. Computerization allows great flexibility in how geologic data can be organized, presented, and updated. The value of this technology is reflected in this Technical Memorandum and the other studies that compose the State Water Plan. Map data has been made available to the public in formats that allow a skilled viewer to access, download and process geospatial data, and work directly with maps and figures present within this and other reports. Computerization greatly facilitated the process of organizing the GIS geologic units into hydrogeologic units and the development of the surface hydrogeology map and associated hydrostratigraphic chart provided as **Plate 2.** The **Plate 2** map of Platte River Basin surface hydrogeology is frequently referenced directly and is used throughout this study as a base for presenting the data compiled for water wells, springs, potential contaminant sources, and potential groundwater development areas. As discussed in **Sections 5.1.3.1** and **6.2**, the GIS-based surface hydrogeology map also allowed a reasonable quantitative estimate of annual recharge to the outcrop areas of aquifers exposed in the Platte River Basin.

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007) proposed a generalized aquifer classification system for the entire state based on the amounts of water a hydrogeologic unit has historically provided for beneficial use. Individual geologic units are assigned to one of seven categories by evaluation of their hydrogeologic characteristics. The statewide classification system distinguishes the following seven hydrogeologic categories:

Major aquifer - alluvial: The highly permeable, unconsolidated, flat-lying sand and gravel deposits that compose the alluvium located along rivers and streams are some of the most productive aquifers in the state and the Platte River Basin. Under favorable conditions these

aquifers can provide well yields of 500-1,000 gallons per minute (gpm). Yields are generally lower, however, in areas where the deposits are thin, contain abundant fine-grained material, are located at higher elevations or hydrologically isolated from active streams (e.g., terrace deposits). Flow through unconsolidated material occurs through primary (intergranular) porosity. Where the alluvial aquifer is hydraulically connected with an active stream, direct infiltration from the stream provides most of the groundwater in storage, and alluvial aquifer water quality reflects the water quality of the stream, with modification by the mineral composition of the aquifer matrix. Where discharge from shallow bedrock aquifers is a primary source of alluvial-aquifer recharge, surface water quality is similarly influenced.

Major aquifer - sandstone: These consolidated bedrock formations, composed primarily of permeable coarser-grained lithologies, such as sandstone and conglomerate, commonly supply useable quantities of groundwater. In some cases, sandstone aquifers yield large quantities of good-quality groundwater. Most of the groundwater stored in these aquifers is held in the sandstones' primary porosity. Porous flow is generally dominant; however, fracture flow can be significant in structurally deformed areas. Within the interior lowland basin areas, the sandstone aquifers are mostly horizontal and some are widespread. Relatively thick Tertiary sandstone sequences that compose the High Plains aquifer system of southeast Wyoming are the most productive sandstone aquifers in the Platte River Basin. Older Mesozoic and Paleozoic sandstone aquifers exposed around the perimeters of the Platte River Basin structural basins commonly dip into the basins (**Plates 1** and **2**) and may contain accessible groundwater resources for several miles basinward of the outcrop areas. Groundwater quality tends to decrease with increasing depth into the basins. Some sandstone aquifers exhibit poor yields due to local heterogeneity, high content of fine-grained material, cementation, and lack of fractures. Layers and lenses of sandstone (and coarser lithologies) are generally the most productive intervals; however, coal beds and other strata can also yield substantial groundwater. Where sandstone layers are not thick and widespread but rather heterogeneous and discontinuous, wells must penetrate several individual water-bearing strata to provide adequate flow for the intended use.

Major aquifer – limestone: Carbonate formations are composed primarily of Paleozoic and lower Mesozoic limestone or dolomite that occur throughout Wyoming and are present in all seven major river basins. Limestone aquifers exhibit variable potential for development as wells can produce low yields up to very large quantities of good-quality water. Localized areas of vigorous groundwater flow and high productivity are present where enhanced secondary permeability has developed along solution-enlarged fractures caused by structural deformation and groundwater circulation. These aquifers are exposed primarily along the structural basin margins in the Platte River Basin (**Plate 2**), where deformation and potential for vigorous recharge and groundwater circulation are most prevalent. Examples include the Madison Limestone, the Casper Formation, and the Bighorn Dolomite. Depending on the degree of enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles basinward of their outcrop areas. However, they generally are more deeply buried than the overlying sandstone aquifers and access to them becomes progressively difficult as burial depths increase basinward.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). Higher yields are available at some locations depending on local hydrogeologic and recharge conditions. Water quality in the minor aquifers varies from good to poor. The minor aquifers are typically thinner, more heterogeneous, have lower yields, and are less laterally extensive than the major aquifers. Similar to other aquifer types, outcrop areas are characterized by generally better circulation and groundwater quality, both of which deteriorate, in many cases, rapidly with depth.

Marginal aquifer: These consolidated bedrock formations host mostly low-yielding wells (1-5 gpm) that may be suitable for domestic or stock use. Sandstone beds are the primary source of groundwater in marginal aquifers, although

fractured fine-grained strata and coal seams yield water locally. Marginal aquifers rarely yield substantial quantities of groundwater, and then only under favorable local conditions. The permeability of marginal aquifers is generally low enough that in some areas they also function as minor (leaky) confining units.

Major confining unit: These consolidated bedrock formations are composed primarily of thick layers of marine shale that hydraulically separate underlying and overlying aquifers on a regional scale. These are some of thickest and most widespread formations in Wyoming. Because of their high clay content, these strata are generally less brittle than other lithologies and therefore less subject to fracturing that could enhance permeability. These units typically yield little or no groundwater, and the groundwater that is produced is commonly of poor quality. Rarely, low-yield wells that produce small quantities of useable groundwater have been completed in isolated zones in confining units. The crystalline Precambrian rocks that underlie the basins and crop out in the surrounding mountain ranges throughout Wyoming constitute the basal confining units below the sedimentary basins and represent the lower limit of groundwater circulation. In and near the upland outcrop areas, these rocks possess enough fracture permeability to sustain springs and low-yield wells that provide good-quality groundwater.

Unclassified: These geologic units are of small extent and lack adequate data for hydrogeologic classification.

The Wyoming Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007; Figure 4-9) classified the Platte River Basin geologic units as follows:

Major Aquifer - Alluvial

Quaternary alluvium

Major Aquifer - Sandstone

Wasatch and Wind River Formations
Fort Union Formation
Lance Formation
Fox Hills Formation
Cloverly/Dakota Formations

Major Aquifer - Limestone

Casper Formation, Tensleep Sandstone, Minnelusa Formation, and Hartville Formation
Madison Limestone and Bighorn Dolomite

Minor Aquifer

Quaternary non-alluvial deposits
Arikaree Formation
Mesaverde Formation or Group
Frontier Formation
Gallatin Formation, Gros Ventre Formation, and Flathead Sandstone

Marginal Aquifer

White River Formation
Sundance Formation

Major Aquitard (Confining Unit)

Meeteetse Formation and Lewis Shale Cody Shale, Pierre Shale, Steele Shale, Niobrara Formation, Baxter Shale, and Carlisle Shale
Thermopolis Shale, Mowry Shale, and Aspen Shale
Chugwater and Goose Egg FormationsPrecambrian rocks

While the 2007 Wyoming Statewide Framework Aquifer Classification System provides a general summary of the groundwater resources of the seven major drainage basins of Wyoming, the updated individual river basin plans provide a greater level of hydrogeologic detail and analysis. **Plate 2** summarizes the hydrogeology developed in this study for the Platte River Basin. Correlations between the 2007 Wyoming Statewide Framework Water Plan aquifer classification system (WWC Engineering, Inc. and others, 2007), and the hydrogeology presented in this study are explained on the hydrostratigraphic charts found on **Plates J, K, M, S, T,** and **U** and **Figure 7-2.**

5.4 Influence of structure on groundwater circulation

Huntoon (1993) presented a summarized conceptual model for "The Influence of Laramide

Foreland Structure on Modern Ground-water Circulation in Wyoming Artesian Basins" that he and several of his graduate students at the University of Wyoming developed over several years of research and field work, largely within the Bighorn and Platte River Basins. The central thesis of their research is that large-displacement thrust faults, reverse-fault-cored anticlines, and associated fractures and anisotropic permeability that developed during Laramide compressional deformation strongly influence groundwater recharge and circulation through the major Paleozoic and lower Mesozoic major carbonate aquifers exposed along the major uplifts of the Wyoming foreland basins. The main components of this conceptual model include:

- The Wyoming foreland mountain ranges consist of large-scale uplifts situated atop large-displacement (thousands of feet) basement thrust faults with fault-severed strata on one side and homoclinal dipping strata on the other. The cross sections shown in **Figures 4-7, 4-10** and **4-15** provide good examples of this typical Laramide structural pattern, particularly the fault-severed strata. The cross sections shown in **Figures 4-11, 4-12, 4-13** and **4-14** present views of Laramide basin architecture along the homoclinal west side of the Laramie Mountains especially the upland exposure and basinward dip and burial of the major carbonate aquifers.
- The compressional processes that shaped the basins during the Laramide orogeny also produced smaller structures such as reverse- and thrust-cored asymmetric anticlines within the basins.
- Laramide deformation and erosion established the hydraulic boundaries of groundwater circulation in Wyoming's foreland structural basins.
- Groundwater circulation is not only controlled by the Laramide structures, but also alters the hydrogeology of them:
    - Fracture (secondary) permeability within carbonate strata associated with faulting and folding has been enhanced by carbonate dissolution.
    - Any fracture can potentially enhance permeability, even if formed in a compressional environment (e.g., trough of a synclinal fold).
    - Fractures parallel or oblique to the crests of folds, along with bedding-plane partings, formed during anticlinal folding. These fractures are extensional and have maximum potential for developing solution-enhanced, highly anisotropic permeability. Where it develops, extensional fracture permeability dominates local groundwater circulation. Groundwater circulation within areas of highly anisotropic fracture permeability along the crests of anticlinal folds is inhibited across the structural trend and tends to converge within the fractures developed along and parallel or oblique to the folds.
    - Large-displacement thrust faults and smaller displacement reverse and normal faults can sever an aquifer's hydraulic connection between recharge areas and the deeper basin interior. Separate groundwater circulation systems develop in the hanging wall and the footwall of major uplift-bounding, large-displacement faults.
    - Within synclinal folds the rocks are highly compressed, out-of-synclinal thrusting thins the strata, interstitial porosity is destroyed, and fractures are compressed rather than open.
    - Faults can act as either conduits or barriers to flow.

- Karst developed along pre-existing fractures within the major carbonate aquifers during erosion and exposure of the recharge areas, and ongoing karstification, have greatly enhanced the permeability of these aquifers around the perimeters of Wyoming's Laramide basins.
- To a lesser extent, paleokarst, developed when the carbonate strata were exposed

during Late Mississippian time, has enhanced permeability; however, the paleokarst has largely been filled in with sediments that reduce permeability.

- Where permeability is not enhanced by solution-enlarged fractures, which includes by far most of the subsurface extent of the major carbonate aquifers, intercrystalline permeability is very low.
- Groundwater circulation is primarily parallel to bedding. Vertical circulation within the deep artesian basins is very limited except along faulted and fractured anticlines where the permeability of confining units is enhanced.
- Brittle strata (sandstone, limestone, and dolomite) are more prone to fracture during deformation than fine-grained strata (shale, claystone, and mudstone). Fine-grained strata are also more plastic, and small fractures within these units tend to close and seal under compaction.
- Artesian pressure within the basins increases with depth as the recharge areas of the deeper major carbonate aquifers are exposed at generally higher elevations in the surrounding mountain ranges.
- Large production from the major carbonate aquifers is limited to local areas of large solution-enhanced permeability (modern karstification) developed within and down gradient of recharge areas along homoclinal (not fault-severed) flanks of the Laramide uplifts where these aquifers are exposed. How far conditions favorable for large yields of acceptable-quality water extend into the basins depends on the trend and continuity of the controlling structure. Large anticlines trending normal or slightly oblique to the perimeter of the basin will generally provide the greatest recharge to the deeper basin and the best opportunities for high-yield wells.
- Although homoclinal margins exhibit hydraulic and stratigraphic continuity, areas that lack subsidiary structures and associated fracturing of the carbonate aquifers have had less opportunity to develop solution-enhanced permeability and therefore accept less recharge. With less groundwater circulation, dissolution-enhanced permeability in recharge areas does not continue into the basins due to diagenetic processes such as compaction, cementation and recrystallization that destroy porosity and permeability; therefore, transmissivity decreases progressively basinward, and recharge is rejected at springs at the base of the mountains, generally near the location where the carbonate aquifers become covered by a significant confining unit. The difference in diagenetic conditions between recharge areas and the basins increases over time proportional to groundwater circulation (more circulation causes increased dissolution). Nevertheless, homoclinal areas where carbonate aquifers exhibit significant karstification may be favorable groundwater development prospects.
- Groundwater in the major carbonate aquifers at homoclinal basin margins is generally of good quality, and high yields can be obtained under the right conditions.
- In areas where recharge is rejected, surface water and groundwater are interconnected.
- Updip areas of the exposed carbonate aquifers may be only partially or intermittently saturated, and the greater topographic relief of the outcrop areas may limit access to optimal drilling locations (tops of anticlines, adjacent to faults).
- The characteristics that make local exposures of the carbonate aquifers optimal for recharge (good exposures, fracture permeability) also make them highly vulnerable to contamination.
- The synclinal areas of folds and the footwall sides of fault-severed aquifers are not good prospects for groundwater development.
- Computer models of the major carbonate aquifers (and petroleum reservoirs) in the Wyoming foreland basins must

account for the highly anisotropic trends of permeability and transmissivity to accurately predict yield, drawdown, and other production characteristics.

The conceptual model, described above has obvious implications for groundwater exploration and development, and these concepts have been utilized in groundwater development projects throughout the state. **Appendix B** lists Wyoming Water Development projects that have implemented this exploration model. Clearly, identifying and mapping structures in groundwater prospects in the major carbonate aquifers and other aquifers considered for high yield groundwater development would be an important aspect of any groundwater exploration project in the Platte River Basin. Groundwater circulation in the major carbonate aquifer systems of the Platte River Basin is discussed further in **Chapter 7**. Several of the components of the conceptual model described above are illustrated in **Figure 5-1**.

5.5 Conceptual models of deep basin groundwater flow

The fate of groundwater that flows downgradient of its aquifer outcrops and into the deeper parts of a structural basin is not well understood. Several conceptual models have been developed over the past four decades to explain deep groundwater circulation in the typical Rocky Mountain Laramide Basin. Richter (1981a, p. 83, Figure V-3) proposed that within all basin aquifers, down to the surface of the Precambrian basement, small flows continued from outcrop areas on the basin flanks to the center of the basin and thence upward toward ground surface, in response to the strong vertical gradient that develops with progressive downgradient flow into the basin.

In contrast, oil and gas geologists and engineers have developed several generally similar exploration models, variously referred to as "Basin Centered Gas Systems" (BCGS), "Deep Basin Gas Systems," "Tight Gas Systems," and "Continuous Gas Systems," to name a few of the most popular (Shanley and others, 2004), that would preclude Richter's (1981a) groundwater-flow model.

5.5.1 Implications of the basin centered gas systems exploration model for deep-basin groundwater resource potential

The relevant hydrogeologic aspect of BCGS models is that the deeper volumes of Rocky Mountain Laramide basins (and other basins worldwide) are characterized by multi-phase fluid-flow systems of water, liquid hydrocarbons, and natural gas; with the gas phase typically anomalously pressured relative to hydrostatic pressure. Within these multi-phase flow systems, the formation's permeability to water (generally brine) decreases as the proportion of gas and liquid hydrocarbon phases increase to the extent that groundwater essentially will not flow. This condition, commonly referred to as "irreducible water saturation," is consistent with the very low water production rates typically observed by oil and gas producers from BCGS reservoirs, especially fine-grained reservoirs. Within BCGSs, groundwater can be essentially immobile over a wide range of conditions even where it is a significant fraction of the fluid occupying the pore space, especially in low-permeability rocks. In multi-phase flow systems, permeability relationships are complex and generally lower for all fluids in proportion to their percent saturation of the total fluid. Heterogeneous lithology is commonly associated with patchy saturation.

Surdam and others (2005) summarizes the BCGS conceptual model and the following characteristics common to these hydrocarbon systems:

- Anomalously pressured (both high and low) compartmentalized BCGS reservoirs are separated from the overlying normally (hydrostatic) pressured, single-phase, meteoric groundwater-flow system by a regional pressure surface boundary.
- There is a significant change in water chemistry and thermal regime across the pressure surface boundary; below the surface, meteoric flow is precluded, water quality declines toward brine composition, and temperature increases along the geothermal gradient. Higher temperatures enable increased dissolution of rock matrix minerals and lower water quality.

- Capillary displacement pressure increases by several orders of magnitude below the surface, especially within fine-grained strata. Increased displacement pressure significantly reduces groundwater flow across the surface, essentially isolating the two flow regimes. The resulting compartmentalization forms isolated flow systems below the surface.

The pressure surface boundary in Rocky Mountain Laramide basins is generally encountered at approximately 8,000 feet, but can vary by thousands of feet of relief related to the formation of "gas chimneys," the presence of large-scale structures, and stratigraphy. Although poor water quality and high drilling costs generally limit groundwater development to depths much less than 8,000 feet, it is clear that under the BCGS model, except for brine production, the development of deep-basin (below the pressure surface) groundwater resources (unrelated to mineral production) is not feasible. In addition, circulation within the interval from above the surface to current groundwater development depths would be complicated by high relief on the boundary surface, and development would generally be impractical. In many cases BCGSs have a base above the Precambrian basement, and the interval between the BCGS and basement is normally pressured. Although it is possible that meteoric water circulates to great depth in these areas, the depth, temperature, low permeability (from compaction) and poor water quality would preclude groundwater development.

5.5.2 Deep-basin groundwater resource development

In actuality, it may make little difference whether deep groundwater circulation is better described by the BCGS or Richter model because the volumes entering the deep parts of a Laramide basin may be quite small. Huntoon (1983a, b. c) noted that flows into the deep basin constitute only small fractions of the recharge received over basin margin outcrops due to basinward decreases in aquifer permeabilities; the largest part of recharge is rejected as discharge from springs located near the contact of the aquifer outcrop (recharge area) and the overlying confining unit. This hypothesis is supported by numerical simulation models used to study regional flow in other structural basins.

A groundwater flow model developed by Belitz and Bredehoeft (1988) calculated that only 64 cfs (46,000 acre-feet) move into the basin deeps of the 200,000 mi^2 regional flow system comprised of the Denver-Julesburg Basin and its associated uplifts. A similar model developed by Downey (1982) estimated deep basin flows of 77 cfs for the 300,000 mi^2 regional aquifer that includes the Williston Basin of North Dakota. If the low flow rates calculated for these large basins are generally characteristic of Laramide basins, then proportionate deep basin regional flows in the 26,289 mi^2 Platte River Basin would be quite small and preclude groundwater development at production rates sufficient to justify the costs of deep basin drilling and production. Furthermore, the rapid degradation of water quality observed in deep basin aquifers would require treatment to make deep groundwater resources potable.

In summary, none of the conceptual models of deep groundwater circulation, discussed above, preclude the evaluation of Platte River Basin groundwater resources based on the recharge and water balance **(Chapters 6 and 8)** approach used in this study, especially in light of the limited amount of data available relative to the size and diversity of the Platte River Basin hydrogeologic system. However, the possibility that deep basin flows could be quite small should lead groundwater professionals to reconsider the concept of safe yield with respect to the effects that further groundwater development may have on surface water flows and water rights holders.

5.6 Natural groundwater quality and hydrogeochemistry

The practical availability of a groundwater resource depends on a combination of hydrologic, technical, legal, institutional, and cultural factors. The feasibility of development and potential uses for a groundwater resource are primarily dependent on water quality. Groundwater quality data for the Platte River Basin hydrogeologic units **(Section 5.6)**, was compiled for this study by the USGS

from several sources. The data confirms that the best quality groundwater is generally found in regions that are closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulation through the aquifer. Factors that affect groundwater quality include the types and density of vegetation in recharge areas, and the mineral composition, grain size, transmissivity, rate of circulation, and temperature of the vadose zone and aquifer matrix. This generalization is more applicable to the "minor" and "marginal" aquifers of the Platte River Basin than to the "major aquifers," within which groundwater circulation is often substantially more vigorous. Groundwater quality in the Platte River Basin varies from fresh, with total dissolved solids (TDS) less than 1,000 mg/l, suitable for any domestic purpose, to briny, unsuitable for virtually any use, with TDS greater than 200,000 mg/l from deep oil field aquifers.

In the absence of irrigation, most alluvial aquifers receive recharge from hydrologically connected streams and underlying and adjacent bedrock formations. Irrigation can dominate recharge when application is active. Direct precipitation can also add to recharge, but due to high evapotranspiration rates in the basin interiors, the amount of precipitation that reaches the water table is diminished, sometimes severely. Where recharge from streams dominates, groundwater quality is generally good. Sand, gravel, and other aquifer materials filter sediment, bacteria, and some contaminants from surface waters, producing water that is clear and with a chemical composition that reflects the composition of the source waters. Where bedrock recharge sources dominate alluvial groundwater quality reflects that of the surrounding formations in proportion to their contribution, commonly at a higher TDS concentration than when recharge is from surface waters. Irrigation water also affects groundwater quality in proportion to its TDS composition. In addition, irrigation water applied to permeable soil that has not been naturally saturated for millennia will dissolve, mobilize, and concentrate soluble minerals, primarily salt. Irrigation return flows can degrade water quality in streams.

Bedrock aquifers receive recharge through the infiltration of precipitation, by discharge from adjacent bedrock and alluvial formations, and from surface waters, including irrigation. In general, recharge is dominated by precipitation in outcrop areas where there is no natural surface water or irrigation. Recharge from surface water is prevalent along streams and associated saturated alluvial deposits; however, groundwater discharge from bedrock to streams that support baseflow is also common throughout the Platte River Basin. Recharge of bedrock aquifers from streams is generally restricted to periods of very high flow and flooding. Groundwater developed in bedrock aquifers close to recharge areas or at shallow depth may be of high quality, regardless of the host geologic unit. As water flows deeper into the basins, it generally becomes more mineralized. Calcium-bicarbonate type water is dominant in and near recharge areas, whereas sodium levels generally increase relative to calcium, and chloride is dominant over bicarbonate in deeper aquifers. In general, groundwater quality tends to be better in more productive bedrock aquifers because more active groundwater circulation provides less opportunity and time for minerals present in the rock to dissolve.

Sections 5.6.1.1 – 5.6.1.5 contain descriptions of the methods used to access, screen, and statistically summarize water quality data for this report. Detailed discussion of water quality analyses of samples collected from the Platte River Basin aquifers and their component geologic and lithostratigraphic units is provided in **Chapter 7**.

5.6.1 Groundwater quality

This section of the report describes regulation and classification of groundwater in Wyoming; groundwater-quality standards used in this report for descriptive purposes; and how data on chemical characteristics of hydrogeologic units in the Platte River Basin groundwater study were accessed, compiled, screened, and statistically summarized.

Groundwater quality in Wyoming is regulated by two agencies. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division (WQD) regulates groundwater quality in Wyoming, and the U.S. Environmental Protection Agency (USEPA) Region 8 Office, headquartered in Denver, Colorado, regulates the

public water systems located within Wyoming. Each agency has established groundwater standards, and revises and updates them from time to time.

Groundwaters in Wyoming are classified with respect to water quality in order to apply these standards. The State of Wyoming through the WDEQ/WQD has classified the groundwaters of the state, per *Water Quality Rules and Regulations, Chapter 8 – Quality Standards for Wyoming Groundwaters* (Wyoming Department of Environmental Quality, 1993), as:

- Class I Groundwater of the State – Groundwater that is suitable for domestic use.
- Class II Groundwater of the State – Groundwater that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate for such use.
- Class III Groundwater of the State – Groundwater that is suitable for livestock.
- Class Special (A) Groundwater of the State – Groundwater that is suitable for fish and aquatic life.
- Class IV Groundwater of the State – Groundwater that is suitable for industry.
- Class IV(A) Groundwater of the State – Groundwater that has a total dissolved solids (TDS) concentration not in excess of 10,000 milligrams per liter (mg/L). This level of groundwater quality in an aquifer is considered by the USEPA under Safe Drinking Water Act (SDWA) provisions as indicating a potential future drinking water source with treatment.
- Class IV(B) Groundwater of the State – Groundwater that has a TDS concentration in excess of 10,000 mg/L.
- Class V Groundwater of the State – Groundwater that is closely associated with commercial deposits of hydrocarbons (oil and gas) (Class V, Hydrocarbon Commercial) or other minerals (Class V, Mineral Commercial), or is a geothermal energy resource (Class V, Geothermal).
- Class VI Groundwater of the State – Groundwater that may be unusable or unsuitable for use.

5.6.1.1 Standards of groundwater quality

Groundwater quality is compared to four types of USEPA standards: Maximum Contaminant Level (MCL), Action Level (AL), Secondary Maximum Contaminant Level (SMCL), and Lifetime Health Advisory Level (LHA) standards. In assessing suitability for domestic use (Wyoming Class I groundwater), USEPA health-based Maximum Contaminant Level (MCL), Action Level (AL), Secondary Maximum Contaminant Level (SMCL), and Lifetime Health Advisory Level (HAL) standards are used (even though they are not legally enforceable for any of the sampling sites used in this study) (**Table 5-2**). The USEPA MCLs (U.S. Environmental Protection Agency, 2011) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections, or regularly serve at least 25 individuals. The purpose of MCLs is to protect public health by limiting the levels of contaminants in drinking water. MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. They are, however, a valuable reference when assessing the suitability of water for these uses. An AL is the concentration of the chemical, which, if exceeded, requires treatment by the public water supplier (U.S. Environmental Protection Agency, 2011). USEPA SMCLs (U.S. Environmental Protection Agency, 2011) are non-enforceable guidelines regulating contaminants in drinking water that may cause cosmetic effects (such as skin or tooth discoloration) or have negative aesthetic effects (such as taste, odor, or color) in drinking water. USEPA Health Advisory Levels are nonenforceable standards that establish acceptable constituent concentrations for different exposure periods. In this study, concentrations are compared with the lifetime Health Advisory Level (HAL), which is the concentration of a chemical that would not result in any known or anticipated adverse noncarcinogenic health effects over a lifetime of exposure (70 years) (U.S. Environmental Protection Agency, 2011).

Quality standards for Wyoming Class II, Class III, and Class IV groundwater (Wyoming

Table 5-2. Selected groundwater quality standards and advisories.

Physical characteristics and constituents		Groundwater quality and standards: Domestic [1] MCL or AL (USEPA)	Domestic [1] SMCL (USEPA)	Domestic [1] LHA (USEPA)	Agricultural [2] Class II (WDEQ/WQD)	Livestock [2] Class III (WDEQ/WQD)
Physical characteristics	pH (standard units)		6.5-8.5		4.5-9.0	6.5-8.5
Major ions and related characteristics (mg/L)	chloride (Cl^-)		250		100	2,000
	fluoride (F^-)	4	2			
	sulfate (SO_4^{2-})		250		200	3,000
	TDS		500		2,000	5,000
	SAR (ratio)				8	
Trace elements (µg/L)	aluminum (Al)		50-200		5,000	5,000
	antimony (Sb)	6				
	arsenic (As)	10			100	200
	barium (B)	2,000				
	beryllium (Be)	4			100	
	boron (B)			6,000	750	5,000
	cadmium (Cd)	5			10	50
	chromium (Cr)	100			100	50
	cobalt (Co)				50	1,000
	copper (Cu)	1,300 (AL)	1,000		200	500
	cyanide[3] (CN^-)	200				
	iron (Fe)		300		5,000	
	lead (Pb)	15 (AL)			5,000	100
	lithium (Li)				2,500	
	manganese (Mn)		50		200	
	mercury (Hg)	2				0.05
	molybdenum (Mo)			40		
	nickel (Ni)			100	200	
	selenium (Se)	50			20	50
	silver (Ag)		100			
	thallium (Tl)	2				
	vanadium (V)				100	100
	zinc (Zn)		5,000	2,000	2,000	25,000
Nutrients (mg/L)	nitrate (NO_3^-), as N	10				
	nitrite (NO_2^-), as N	1				10
	nitrate + nitrite, as N	10				100
	ammonium (NH_4^+), as N			30		
Radiochemicals (pCi/L)	gross-alpha radioactivity[4]	15			15	15
	strontium-90 (strontium)			4,000 (µg/L)	8	8
	radium-226 plus radium-228	5			5	5
	radon-222 (radon)[5]	300/4,000 (proposed)[5]				
	uranium (µg/L)	30				

[1] Selected from USEPA 2011 edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2011)

[2] Selected from WDEQ, 1993 [revised 2005], Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters, Table 1, p. 9

[3] Trace ion, included with trace elements for convenience

[4] Includes radium-226 but excludes radon-222 and uranium

[5] The 300 pCi/L standard is a proposed MCL, whereas the 4,000 pCi/L standard is a proposed alternative MCL for communities with indoor air multimedia mitigation programs (U.S. Environmental Protection Agency, 1999).

MCL, Maximum Contaminant Level
SMCL, Secondary Maximum Contaminant Level
HAL, Lifetime Health Advisory Level
USEPA, U. S. Environmental Protection Agency
WDEQ-WQD, WDEQ Water Quality Division

N, nitrogen
mg/L, milligrams per liter (ppm)
µg/L micrograms per liter (ppb)
pCi/L, picocuries per liter
SAR, sodium adsorption ratio
TDS, total dissolved solids

Department of Environmental Quality, 1993) also are used for comparisons in this report. Class II groundwater is water that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate. Class III groundwater is water that is suitable for livestock use. Class IV groundwater is water that is suitable for industry. The Class IV standard is a TDS-only standard (10,000 mg/L) that also corresponds to the USEPA underground source of drinking water (USDW) TDS standard established as part of underground injection control (UIC) regulations. These Wyoming standards are designed to protect groundwater that meets the criteria of a given class from being degraded by human activity. They are not meant to prevent groundwater that does not meet the standards from being used for a particular use. Like the USEPA standards, they serve only as guides in this report to help assess the suitability of groundwater for various uses.

5.6.1.2 Sources, screening, and selection of data

Groundwater-quality data were gathered from for 1911-2010 the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010a), the USGS Produced Waters Database (PWD) (U.S. Geological Survey, 2010b), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (Wyoming Oil and Gas Conservation Commission, 2010), the University of Wyoming Water Resources Data System (WRDS) database, and other sources such as consultant reports prepared in relation to development of public water supplies. Methods used to screen data differ among the data sources, but the overall objective of all screening was to identify and remove samples that (1) were duplicates; (2) were not assigned to hydrogeologic units or were assigned to hydrogeologic units that contradicted local geologic information, particularly for shallow wells; (3) had inconsistent water-chemistry information such as poor ion balances or substantially different values of total dissolved solids and the sum of major ions; or (4) were unlikely to represent the water quality of a hydrogeologic unit because of known anthropogenic effects – for example, samples from wells monitoring known or potential point-source contamination sites or mining spoils sites. For some constituent results, zero values were present in the original data set. During sample evaluation, we inferred that these values should have been reported as missing or as censored values. Because a censoring limit was not stored with the historical samples, the zero values were removed from the data sets.

Groundwater-quality data were gathered from the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010a), the USGS Produced Waters Database (PWD) (U.S. Geological Survey, 2010b), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (Wyoming Oil and Gas Conservation Commission, 2010), the University of Wyoming Water Resources Data System (WRDS) database, and other sources such as consultant reports prepared in relation to development of public water supplies. Methods used to screen data differ among the data sources, but the overall objective of all screening was to identify and remove samples that (1) were duplicates; (2) were not assigned to hydrogeologic units or were assigned to hydrogeologic units that contradicted local geologic information, particularly for shallow wells; (3) had inconsistent water-chemistry information such as poor ion balances or substantially different values of total dissolved solids and the sum of major ions; or (4) were unlikely to represent the water quality of a hydrogeologic unit because of known anthropogenic effects – for example, samples from wells that monitor known or potential point-source contamination sites or mining spoils sites. For some constituent results, zero values were present in the original data set. During sample evaluation, we inferred that these values should have been reported as missing or as censored values. Because a censoring limit was not stored with the historical samples, the zero values were removed from the data sets.

Many of the Platte River Basin groundwater sites had been sampled more than once; however, only one groundwater sample from a given site was selected for this study to avoid biasing the statistical results in favor of multiple-sample sites. An exception involved some sets of PWD samples from the same well at different depths and from different hydrogeologic units. In choosing among

multiple samples from a site or well/hydrogeologic-unit combination, either the most recent sample, the sample with the best ion balance, or the sample with the most complete analysis was retained in the final data set.

Groundwater-quality sample analyses from the USGS PWD (U.S. Geological Survey, 2010b) are used in this report. Produced water is water co-produced with oil and gas. The PWD includes samples within the Platte River Basin. Only those PWD samples from a wellhead or from a drill-stem test were used. Samples not assigned to a hydrogeologic unit were removed from the data set. The PWD samples were then screened to retain a single sample per well/hydrogeologic-unit combination. Some samples were removed because their water chemistry was identical to that of other samples, indicating probable duplication of sample records. PWD documentation (U.S. Geological Survey, 2010b) indicated that samples generally had been screened to remove samples showing an ion balance greater than 15 percent—strictly, an imbalance between anion and cation activity of greater than 15 percent. The PWD generally contains chemical analyses for major ions and TDS. According to PWD documentation (U.S. Geological Survey, 2010b), some sample analyses may have reported the sum of sodium and potassium concentrations as sodium concentration alone.

Groundwater-quality sample analyses from the WOGCC database are used in this report. Major-ion balances were calculated for these samples. Samples with an ion balance of greater than 10 percent generally were removed, but some samples with an ion balance of between 10 and 15 percent from areas with few samples were retained.

Some groundwater-quality samples from the WRDS database are used in this report. Samples from wells and springs where information was not available to identify the hydrogeologic unit or the site was not in the USGS NWIS database were removed from the WRDS data set. In addition, WDEQ monitoring wells located at sites of known or potential groundwater contamination were removed because the objective of this study is to describe general groundwater quality based on natural conditions. Samples showing an ion balance greater than 10 percent were removed from the WRDS data set.

Groundwater quality in the Platte River Basin varies widely, even within a single hydrogeologic unit. Water quality in any given hydrogeologic unit tends to be better near outcrop areas where recharge occurs, and tends to deteriorate as the distance from these areas increases (and residence time increases). Correspondingly, the water quality in a given hydrogeologic unit generally deteriorates with depth.

Many of the groundwater-quality samples from Quaternary and Tertiary hydrogeologic units came from wells and springs that supply water for livestock and wildlife. Wells that do not produce usable water generally are abandoned, and springs that do not produce usable water typically are not developed. In addition, where a hydrogeologic unit is deeply buried, that unit generally is not used for water supply if a shallower supply is available. For these reasons, the groundwater-quality samples from the Quaternary, Tertiary, and some Cretaceous hydrogeologic units are most likely biased toward better water quality, and do not represent random samples. Although this possible bias likely does not allow for a complete characterization of the water quality of these hydrogeologic units, it probably allows for a more accurate characterization of the units in areas where they are shallow enough to be used economically.

Many of the groundwater-quality samples used in this study to characterize Mesozoic and Paleozoic hydrogeologic units are produced-water samples from the USGS PWD and WOGCC databases. Although these samples were from oil and gas production areas, we believe that they may have less bias in representing ambient groundwater quality than samples used to characterize Quaternary and Tertiary hydrogeologic units.

5.6.1.3 Water-quality characteristics

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the Platte River Basin, even in water from shallow wells. This is not surprising, given the arid climate and small rate of recharge in much of the study area. High TDS can adversely affect the taste and odor of drinking water, and a high TDS concentration in irrigation water can adversely affect crop production. High TDS concentrations

also cause scale build-up in pipes and boilers. No USEPA MCL is available for TDS, and the USEPA SMCL for TDS is 500 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 2011). The TDS concentration is loosely termed salinity. Groundwater samples are classified in this report in accordance with the USGS salinity classification (Heath, 1983), as follows:

Classification	TDS
Fresh	0–999 mg/L
Slightly saline	1,000–2,999 mg/L
Moderately saline	3,000–9,999 mg/L
Very saline	10,000–34,999 mg/L
Briny	more than 34,999 mg/L

The sodium-adsorption ratio (SAR) represents the ratio of sodium ion activity (concentration) to calcium and magnesium ion activities; it is used to predict the degree to which irrigation water enters into cation-exchange reactions in the soil. High SAR values predict sodium replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR should be used in conjunction with information about the soil characteristics and irrigation practices in the area being examined. The high SAR (greater than 8) of waters in some hydrogeologic units in the Platte River Basin indicates that these waters may not be suitable for irrigation.

Many groundwater-quality samples reviewed for this report also contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA and WDEQ water-quality standards. As expected, produced water (defined in the produced-water sample section, below) commonly exceeded many USEPA and WDEQ standards.

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2011). The USEPA SMCL for sulfate is 250 mg/L (U.S. Environmental Protection Agency, 2011), the WDEQ Class II groundwater (agricultural) standard is 200 mg/L, and the WDEQ Class III groundwater (livestock) standard is 3,000 mg/L.

A high chloride concentration can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops. The USEPA SMCL for chloride is 250 mg/L (U.S. Environmental Protection Agency, 2011), the WDEQ Class II groundwater (agricultural) standard is 100 mg/L, and the WDEQ Class III groundwater (livestock) standard is 2,000 mg/L.

High fluoride concentrations commonly are associated with produced water from deep hydrogeologic units in sedimentary structural basins. Low concentrations of fluoride in the diet have been shown to promote dental health, but higher doses can cause health problems such as dental fluorosis—a discoloring and pitting of the teeth—and bone disease (U.S. Environmental Protection Agency, 2011). The USEPA SMCL for fluoride is 2.0 mg/L, and the MCL is 4.0 mg/L.

Both iron and manganese may adversely affect the taste and odor of drinking water and cause staining of plumbing fixtures. The USEPA has established SMCLs for iron at 300 micrograms per liter (µg/L) and manganese at 50 µg/L (U.S. Environmental Protection Agency, 2011). High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.6.1.4 Statistical analysis

In relation to groundwater quality, analysis has two meanings in this chapter, *chemical analysis* and *statistical analysis*. Chemical analysis of a water sample is the determination (or the description) of the concentration of chemical species dissolved in the water: for example, *the concentration of calcium in the sample is 6 mg/L per liter* (6 milligrams of calcium per liter of water). The chemical analysis may include such physical measurements of chemical characteristics as pH (a measure of hydrogen ion activity). The statistical analysis of a *set* of chemical analyses is the mathematical treatment of the set of data to describe and summarize those data in order to convey certain useful descriptive characteristics: for example, *the calcium concentration in groundwater samples from this formation ranges from 5.0 to 20 mg/L per liter, with a median concentration of 17 mg/L per liter*.

This section describes the approaches we used to compile, analyze, and present water-quality data for samples of groundwater from the Platte River Basin. Supplementary data tables contain all the data used in this chapter—data too numerous for inclusion in the chapter, but available online at (WSGS to eventually add URL here). From these data, we derived *summary statistics* for physical characteristics and chemical quality of groundwater in Platte River Basin hydrogeologic units, as tabulated in **Appendix E** for environmental samples and **Appendix F** for produced-water samples. *Environmental water* is natural groundwater as produced from wellheads and springs; it is not associated with hydrocarbons. *Produced water* is water co-produced (pumped out of the ground) with oil and gas. We also used these data to compare groundwater quality in Platte River Basin hydrogeologic units to USEPA and WDEQ standards for various uses, as the *groundwater-quality standard exceedance frequencies* presented in this report.

Standard summary statistics (Helsel and Hirsch, 1992) for uncensored data were used for physical characteristics and major-ion chemistry (**Appendices E** and **F)**. Standard summary statistics also were included for iron concentrations from produced waters. Censored data are data reported as above or below some threshold, such as "below detection limit" or "less than 1 mg/L." For a very small number of major-ion samples, censored values ("less-than") may have been reported for a major-ion constituent. These censored values were treated as uncensored values at the laboratory reporting limit, level for statistical analysis. For uncensored data sets with a sample size of 1, only a minimum value is reported in **Appendices E** and **F**; for a sample size of 2, minimum and maximum values are reported; for a sample size of 3, minimum, median (50th percentile), and maximum values are reported; for sample sizes of 4 or more, minimum, 25th percentile, median (50th percentile), 75th percentile, and maximum values are reported.

Many nutrient concentrations, trace element concentrations, and radiochemical concentrations were reported as censored values in the environmental waters data set. In some cases, censored values had multiple detection limits. Rather than assign the laboratory reporting level or another arbitrary value to the censored results, the Adjusted Maximum Likelihood Estimation (AMLE) technique was used for statistical analysis of nutrients, trace elements, and radiochemical constituents in this report. The AMLE technique is for left-censored data and computes summary statistics for results with multiple detection limits (Helsel and Cohn, 1988). The technique requires that at least three values must be uncensored for a sample size of three or greater and that the proportion of censored values does not exceed 90 percent in order to compute percentiles. The AMLE technique computes statistics for the interquartile range and determines the maximum uncensored value for the data set; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. For some constituents and hydrogeologic units, water-quality data could not meet the minimum sample size or uncensored value requirements for the AMLE technique. For constituents within a hydrogeologic unit that had a sample size of 1, a minimum value is reported, and for a sample size of 2, minimum and maximum values are reported. In those instances where the sample size was three or greater, but the number of uncensored values was too small, the AMLE technique failed to compute percentiles; therefore, summary statistics are not presented in **Appendix E**. In those cases, although a data set for a constituent and hydrogeologic unit was insufficient for determining summary statistics with the AMLE technique, individual samples could still be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedance frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedance frequencies were calculated and reported as a percentage for a hydrogeologic unit. When only one sample exceeded a standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent'. Groundwater-quality standard exceedance frequencies were determined using the filtered analyses for a constituent because filtered analyses were more commonly (or frequently the only) analyses available. Only

samples for a constituent that were analyzed at a censoring reporting level that was equal to or less than the specific groundwater-quality standard for that constituent were included in the exceedance analysis. For example, if there were five samples analyzed for manganese and the results were <10 µg/L, <20 µg/L, 53 µg/L, 67 µg/L, and <100 µg/L, only the four samples with results of <10 µg/L, <20 µg/L, 53 µg/L, and 67 µg/L can be compared to the SMCL of 50 µg/L for manganese. The sample with the value of <100 µg/L cannot be used because it cannot be determined if its value was less than 50 µg/L or greater than 50 µg/L. For this example, the groundwater quality exceedance text would indicate that 50 percent of samples exceeded the SMCL of 50 µg/L. Manganese would not be included in the appendix for the hydrogeologic unit in this example because values were too censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the data set was not met. Descriptions of the constituents that were included in the statistical summaries for environmental water samples and produced-water samples are summarized in the next section.

5.6.1.4.1 Environmental water samples

Environmental water samples ("environmental waters") are from wells of all types except those used for resource extraction (primarily oil and gas production) or those used to monitor areas with known groundwater contamination. The environmental water samples used in this report were compiled from the USGS NWIS database (U.S. Geological Survey, 2010), the WRDS database, and other sources such as consulting engineers' reports related to water-supply exploration and development. Physical characteristics, major-ion chemistry, nutrients, trace elements, and radiochemicals are summarized for environmental waters.

Physical characteristics of environmental waters, which are generally measured in the field on unfiltered waters, include dissolved oxygen (reported in milligrams per liter), pH (reported in standard units), and specific conductance (reported in microsiemens per centimeter at 25 degrees Celsius). If field values of pH and specific conductance were not available, laboratory values were used.

Major-ion chemistry of environmental waters, comprising major ions and associated characteristics or constituents, was reported as laboratory analyses of filtered waters (or constituents were calculated from laboratory analyses). Major-ion constituents and related characteristics include hardness (calculated and reported as calcium carbonate), dissolved calcium, dissolved magnesium, dissolved potassium, sodium-adsorption ratio (calculated), dissolved sodium, alkalinity (reported as calcium carbonate), dissolved bromide, dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and total dissolved solids (TDS). These constituents are reported in milligrams per liter, and with the exception of TDS, the term "dissolved" is not used for the major ion constituents analyzed in filtered water samples hereafter in this report.

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) was commonly used. If a laboratory value was not available, a TDS value was calculated by summing concentrations of individual constituents (if complete analyses were available). For this report, a filtered laboratory value of alkalinity was used. If that was not available, an unfiltered laboratory value of acid-neutralizing capacity (ANC) was used for alkalinity; if that constituent was not available, a filtered field value of alkalinity was used; and if that was not available, an unfiltered field ANC value was used to report alkalinity.

Nutrient constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved ammonia (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved organic carbon, dissolved orthophosphate (reported as phosphorus), and dissolved phosphorus (reported as phosphorus). In addition, nutrient constituents analyzed in a laboratory using unfiltered waters that were included in the summary statistics are ammonia (reported as nitrogen), ammonia plus organic nitrogen (reported as nitrogen), nitrate (reported as nitrogen), nitrate plus nitrite (reported as nitrogen), nitrite (reported as nitrogen), organic

nitrogen (reported as nitrogen), total nitrogen (reported as nitrogen), organic carbon, and total phosphorus (reported as phosphorus). Separate summary statistics were calculated for each constituent and phase that was analyzed. The term dissolved is not used for nutrient constituents analyzed in filtered water samples hereafter in this report. The term 'unfiltered' is used with constituents that were analyzed from unfiltered water hereafter in this report. These constituents are reported in milligrams per liter.

Trace element constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved constituents of aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, selenium, strontium, vanadium, and zinc. In addition, total iron (unfiltered) and total manganese (unfiltered) were included in the analysis. Separate summary statistics were calculated for each constituent and phase that was analyzed. The term dissolved is not used for trace element constituents analyzed in filtered water samples hereafter in this report. The term 'unfiltered' is used with constituents that were analyzed from unfiltered water hereafter in this report. These constituents are reported in micrograms per liter.

Radiochemical constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved alpha radioactivity (using thorium-230 curve or natural uranium curve method), gross beta radioactivity, dissolved radium-226 (using an unspecified or a radon method), dissolved radium-228, and dissolved uranium (natural); the term "dissolved" is not used for the radiochemical constituents analyzed in filtered water samples hereafter in this report. In addition, radon-222 (unfiltered) (referred to herein as "radon") and tritium (unfiltered) were included in the analysis. All radiochemical constituents are reported in picocuries per liter except uranium, which is reported as micrograms per liter.

5.6.1.4.2 Produced-water samples

Produced-water samples are from wells related to natural resource exploration and extraction (primarily oil and gas production). Produced-water data were compiled from the WOGCC database, the USGS PWD, and the other sources listed under *environmental water samples*. Physical characteristics, major-ion chemistry, and the trace elements are summarized for produced waters. Nutrients and radiochemical data were not included in the statistical analysis because they were reported with the chemical analyses of just a few isolated samples.

Physical characteristics, major-ion chemistry, and trace elements summarized for produced waters were generally the same as for environmental waters, with some exceptions. In the produced-waters data set, the water phase (filtered or unfiltered) was not reported with the data. For physical characteristics, only pH (in standard units) was statistically analyzed. The source (laboratory or field) of the pH values was unknown. Major-ion chemistry constituents and related characteristics statistically analyzed are calcium, magnesium, potassium, sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, sulfate, and total dissolved solids. The method for determining total dissolved solids was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter. For trace elements, iron was the only constituent that was routinely analyzed in samples. Other trace elements were analyzed in just a few isolated samples and thus were not statistically analyzed. Iron concentrations in the original data set were reported in milligrams per liter; we converted them to micrograms per liter for the statistical summary.

5.6.1.5 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Platte River Basin study area are plotted on trilinear diagrams (**Appendices G and H**). A trilinear diagram, also frequently referred to as a Piper diagram (Piper, 1944), provides a convenient method to classify and compare water types based on the ionic composition of different groundwater samples (Hem, 1985). Cation and anion concentrations for each groundwater sample are converted to total milliequivalents per liter (a milliequivalent is a measurement of the molar concentration of the

ion, normalized by the ionic charge of the ion) and plotted as percentages of the respective totals into triangles (**Appendices G and H**). The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes a water type or hydrochemical facies (see Back, 1966).

5.7 Aquifer sensitivity and potential groundwater contaminant sources

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the Platte River Basin. It is axiomatic that protecting groundwater from contamination is much more rational and attainable than cleaning it up after it has been impacted through unsound practices.

In 1992 the Wyoming Department of Environmental Quality/Water Quality Division (DEQ/WQD) in cooperation with the University of Wyoming, the Wyoming Water Resources Center (WWRC), the Wyoming State Geological Survey (WSGS), the Wyoming Department of Agriculture (WDA), and the U.S. Environmental Protection Agency, Region VIII (EPA) initiated the Wyoming Ground Water Vulnerability Mapping Project to evaluate the vulnerability of the state's groundwater resources to contamination. This effort resulted in the publication by the Spatial Data and Visualization Center (SDVC) of the *Wyoming Groundwater Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998). While the fundamental goal of the SDVC study was to develop a GIS-based tool to aid in planning, decision-making, and public education, the GIS maps and associated digital databases developed by the project have been used for numerous subsequent, related studies such as updates to the State Water Plan and this present study. The SDVC aquifer sensitivity map and the associated GIS precipitation and recharge data are used in this study to evaluate aquifer-specific recharge **(Chapter 6)**. The methodology and purpose of the 1998 SDVC report are discussed in this section.

Two map products from the 1998 SDVC study are used to evaluate the potential for groundwater contamination in the Platte River Basin: 1) a map of average annual recharge **(Figure 5-2)** and 2) a map of aquifer sensitivity **(Figure 5-3)**. **Figures 5-4** through **5-10** are maps of potential groundwater contaminant sources in the Platte River Basin. Additional discussion on the rationale for and methodology used in developing **Figures 5-1** through **5-10** is provided in **Appendix C**.

5.7.1 The Wyoming Groundwater Vulnerability Assessment Handbook and aquifer sensitivity

The Wyoming Ground Water Vulnerability Mapping Project was initiated to develop GIS-based mapping approaches to: 1) assess the relative sensitivity and vulnerability of the state's groundwater resources to potential sources of contamination, primarily pesticides; 2) assist state and local agencies in identifying and prioritizing areas for groundwater monitoring; and 3) help identify appropriate groundwater protection measures. The *Handbook* distinguishes "groundwater vulnerability" and "aquifer sensitivity" as follows:

- Aquifer sensitivity refers to the relative potential for a contaminant to migrate to the shallowest groundwater, based solely on hydrogeologic characteristics. According to the SDVC, *"Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material between ground surface and the saturated zone of an aquifer and the aquifer matrix. Aquifer sensitivity is not dependent on land use and contaminant characteristics."*
- Groundwater vulnerability considers aquifer sensitivity, land use, and contaminant characteristics to determine the vulnerability of groundwater to a specific contaminant. Because pollutant characteristics vary widely, the SDVC vulnerability assessments assumed a generic pollutant with the same mobility as water.

Aquifer sensitivity and groundwater vulnerability are characteristics that cannot be directly measured but must be estimated from measurable hydrogeologic and contaminant properties and land-use conditions. Because of the uncertainty inherent in the assessment of sensitivity

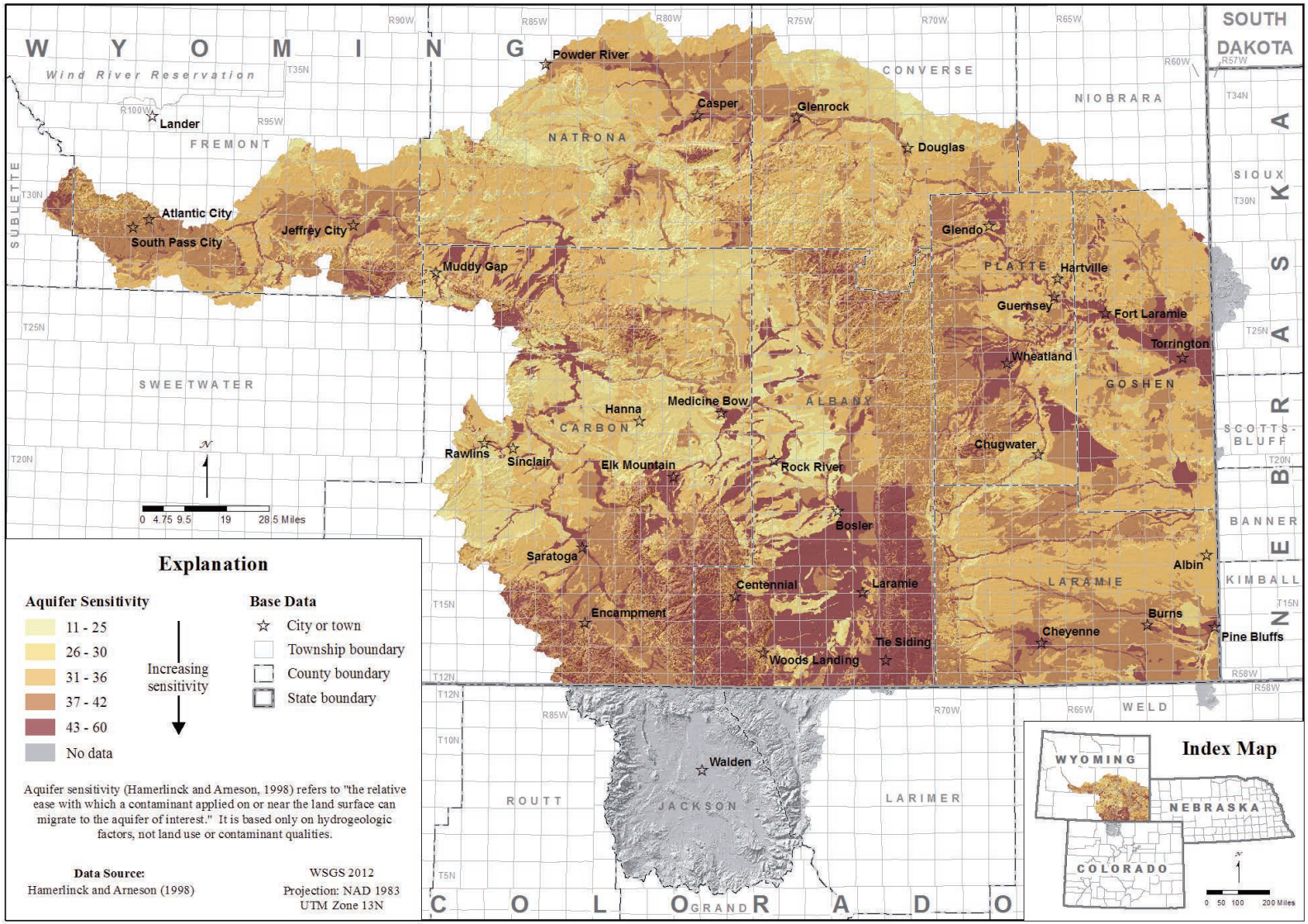


Figure 5-3. Aquifer sensitivity, Platte River Basin, Wyoming.

and vulnerability, these parameters are not expressed quantitatively; but rather, in terms of relative potential for groundwater contamination. Because the SDVC vulnerability mapping assumed a single, generic pollutant, only the map of relative aquifer sensitivity is presented in this study. The aquifer sensitivity map **(Figure 5-3)** may be compared with **Figures 5-4 through 5-10** to identify areas of elevated risk of contamination from specific potential groundwater contaminant sources.

The SDVC study assessed aquifer sensitivity using modified DRASTIC model methodology (EPA, 1993) based on six independent parameters:

- Depth to initial groundwater.
- Geohydrologic setting.
- Soil media.
- Aquifer recharge (average annual).
- Topography (slope).
- Impact of the vadose zone.

The SDVC rates each parameter on a scale from 1 to 10 based on how strongly it affects aquifer sensitivity; a higher value indicates a greater effect. Parameter ratings are then summed to obtain an index of sensitivity that ranges from 6 (lowest risk) to 60 (highest hazard).

There are substantial limitations associated with the SDVC sensitivity analysis and maps. The sensitivity map portrays only a relative assessment of susceptibility to groundwater contamination. The Wyoming sensitivity assessments cannot be compared to similar studies in adjacent states or other areas. The sensitivity assessments are not appropriate for stand-alone site-specific application, and should be supplemented with additional investigations.

Figure 5-3 delineates five sensitivity categories for the Platte River Basin that reflect the relative potential for contaminants to migrate from the ground surface to the uppermost groundwater (water table).

- The highest risk areas **(43-60)** are located primarily over interior basin alluvial deposits, adjacent to rivers, streams, and lakes, and in the highly fractured mountainous belts that surround the basins. The shallow depths to groundwater, high porosities of unconsolidated soils and weathered bedrock, and relatively flat topography place alluvial aquifers at higher risk of contamination. Similarly, heavily fractured bedrock, shallow groundwater within thin soil zones, and high rates of recharge characteristic of mountainous aquifers make them highly vulnerable to contamination.
- Medium-high ranked areas **(37-42)** generally extend from the edges of the highest ranked areas, across adjacent alluvial or foothill zones. Groundwater in these areas generally occurs in deeper, thinner aquifers. The soils in these zones are more mature and have higher clay and loam contents. There is less fracturing in the bedrock exposed in the foothills than in more highly deformed mountainous areas.
- Medium ranked areas **(31-36)** are prevalent in the remaining dry land agricultural and grazing areas of the Platte River Basin. These areas generally have relatively thicker, well-drained, mature soils, rolling topography with minor relief (lower slopes), and generally greater depths to the water table.
- Medium-low ranked areas **(26-30)** are generally characterized by low natural precipitation, low recharge, deep water tables, rolling topography and unfractured bedrock.
- Low ranked areas **(11-25)** have the deepest water tables and lower hydraulic conductivity in the vadose zone. Soils in these areas are generally poor for agriculture due to high clay content, very low average precipitation, or both.

5.7.2 Potential sources of groundwater contamination

Figures 5-4 through **5-10** illustrate potential groundwater contaminant sources in the Platte River Basin. These generally include industrial, retail, private, and public facilities that manufacture, process, use, store, sell, dispose, or otherwise handle substantial volumes of products, wastes, and other substances with physical and

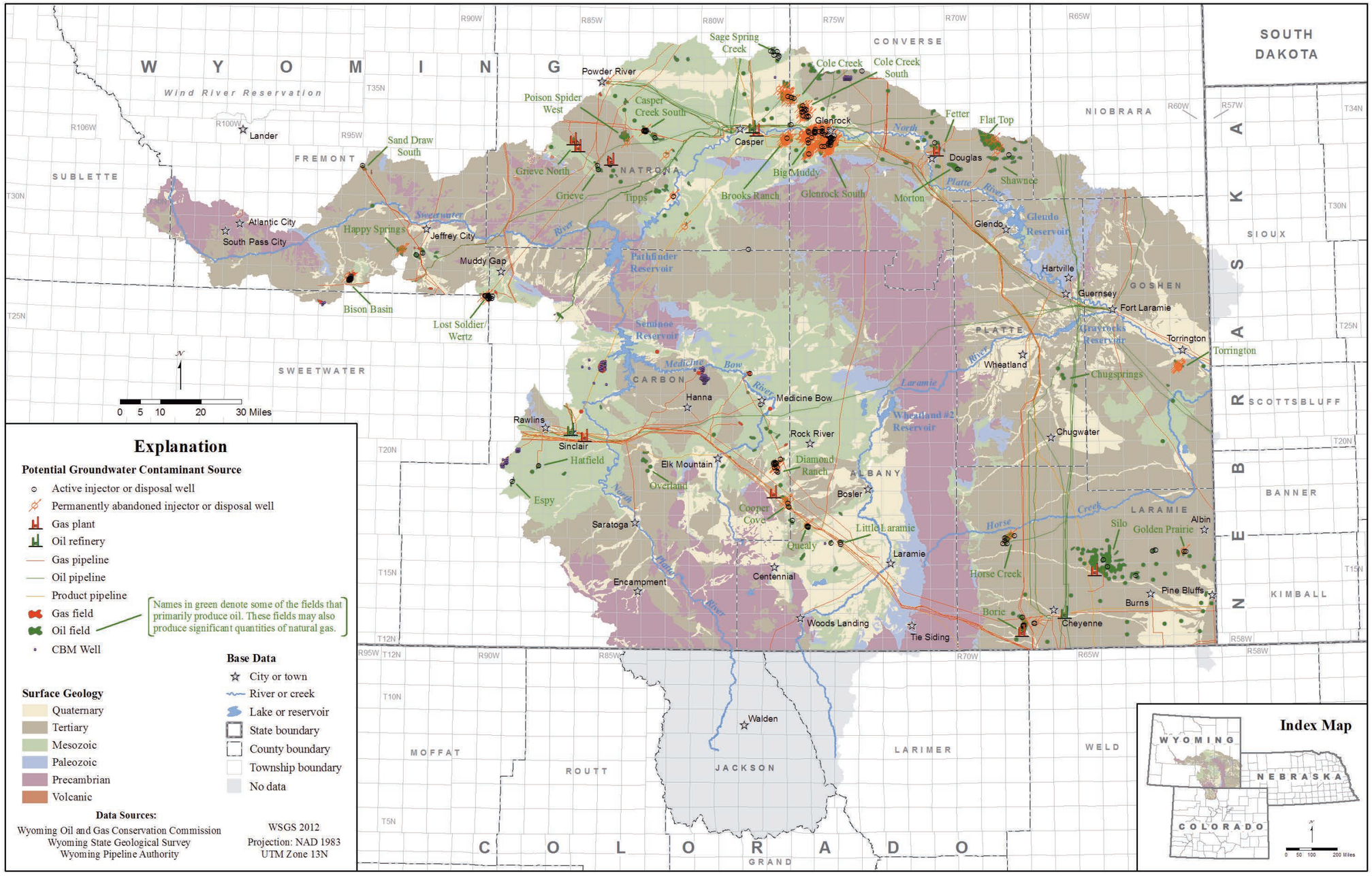


Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, refineries, and Class II injection and disposal wells, Platte River Basin, Wyoming.

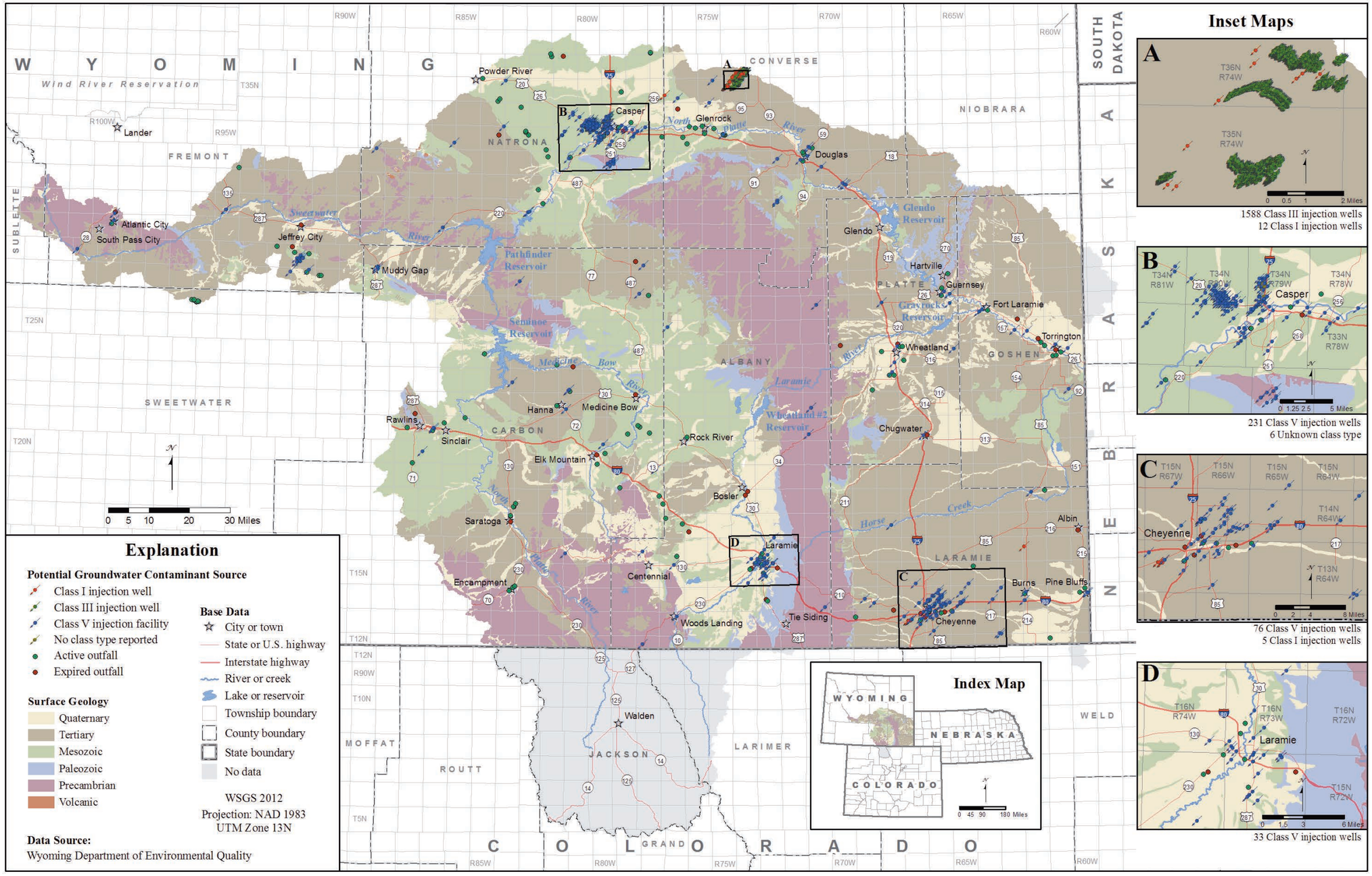


Figure 5-5. Potential groundwater contaminant sources: Class I, III, and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, and active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program, Platte River Basin, Wyoming.

chemical characteristics that, released to the environment, could migrate to the water table. Releases from these facilities would pose a potential threat primarily to unconfined water-table aquifers and the outcrop/recharge areas of commonly confined aquifers. **Figure 5-3** shows areas where migration to the water table is most likely.

The identification and mapping of facilities as potential sources of groundwater contamination ***does not*** imply that they are impacting groundwater resources; however, contamination has been confirmed at specific facilities throughout the state. Generally, these facilities are strictly regulated by one or more government agencies to prevent contaminant releases and to protect groundwater resources, human health, and the environment.

The following regulatory agencies, and the types of facilities that they regulate, provided the geospatial data used to generate **Figures 5-4** through **5-10**:

WDEQ Water Quality Division:

- Contaminated sites regulated under the Groundwater Pollution Control Program
- Class I and V injection wells regulated under the Underground Injection Control (UIC) Program.
- Wyoming Pollutant Discharge Elimination System (WYPDES), formerly National Pollutant Discharge Elimination System (NPDES), discharge points;
- Public owned treatment works (POTWs) and septic systems (Water and Wastewater Program).
- Confined animal feeding operations (CAFOs).
- Pesticides/herbicides (Nonpoint Source Program).
- Underground coal gasification sites.

WDEQ Solid and Hazardous Waste Division:

- Known contaminated sites regulated under the Voluntary Remediation Program (VRP), including orphan sites and brownfield assistance sites.
- Permitted disposal pits and other small treatment, storage, and disposal (TSD) facilities.
- Landfills.
- Above-ground and underground storage tanks.

WDEQ Land Quality and Abandoned Mine Land Divisions:

- Class III injection wells used for mineral extraction;
- Active, inactive, and abandoned mines, gravel pits, quarries, etc.

Wyoming Oil & Gas Conservation Commission:

- Active and abandoned Class II disposal and injector wells.
- Produced water pits.

Wyoming State Geological Survey:

- Oil and gas fields, plants, compressor stations.
- Pipelines.
- Mines (active and inactive).
- Gravel pits, quarries, etc.

The agencies, listed above, were contacted to obtain available data suitable for mapping the various potential contaminant sources. Location data for similar potential contaminant sources were grouped for presentation on an abridged version of the surface hydrogeology map **(Plate 2)**: the groupings in **Figures 5-4** through **5-10** are generally not by agency, but rather by similarity of facilities and presentation considerations, primarily data point density. Some areas of high data density have been scaled up as inserts on the potential contaminant sources maps.

Figure 5-4 – Potential groundwater contaminant sources: Oil and gas fields, pipelines, refineries, and WOGCC Class II injection and disposal wells

- **Oil and gas fields:** Oil and gas exploration, production, processing, and transportation facilities handle large volumes of petroleum hydrocarbons, produced water, and

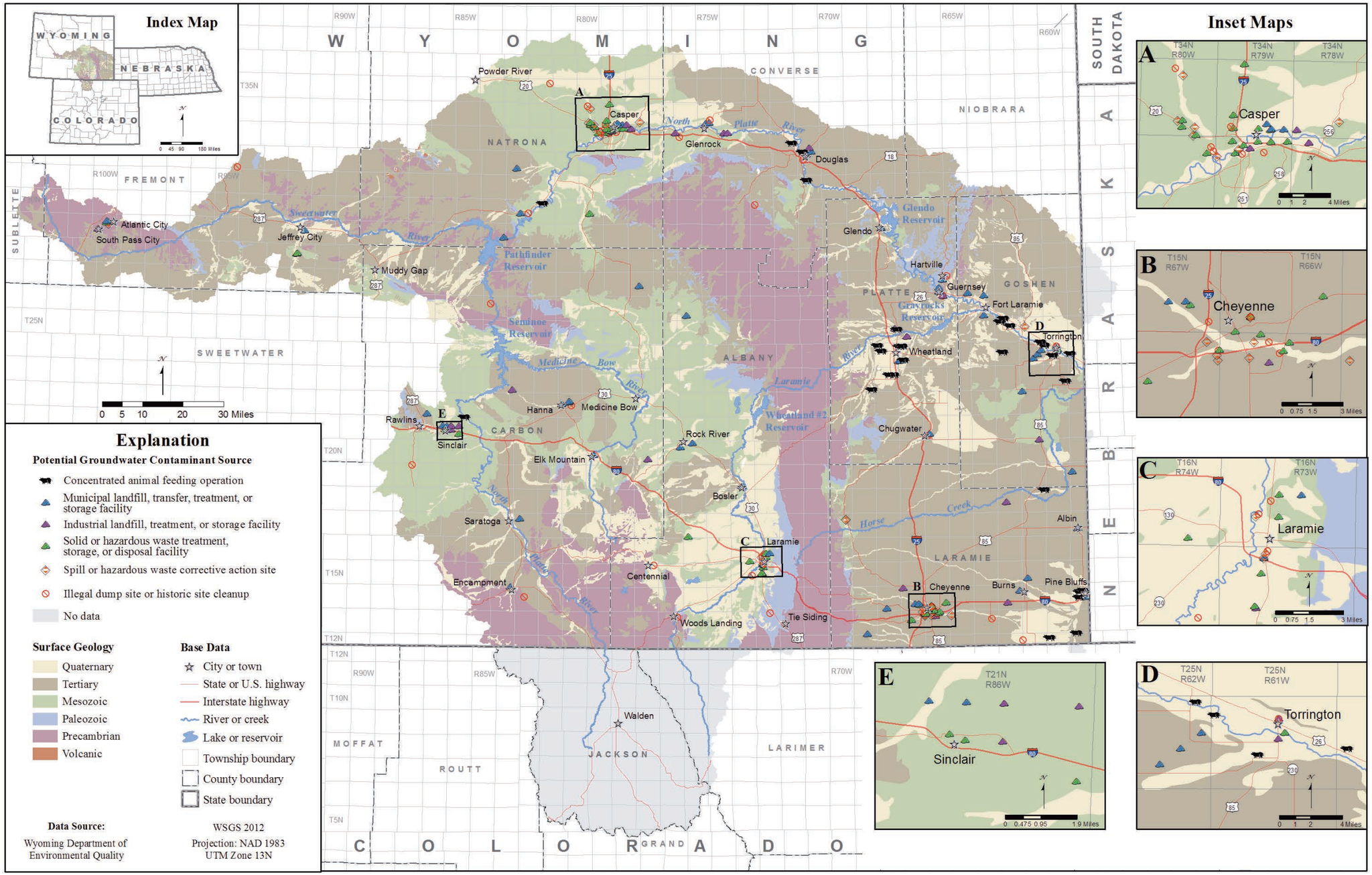


Figure 5-6. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality permitted and inventoried solid and hazardous waste facilities, and concentrated animal feeding operations (CAFOs), Platte River Basin, Wyoming.

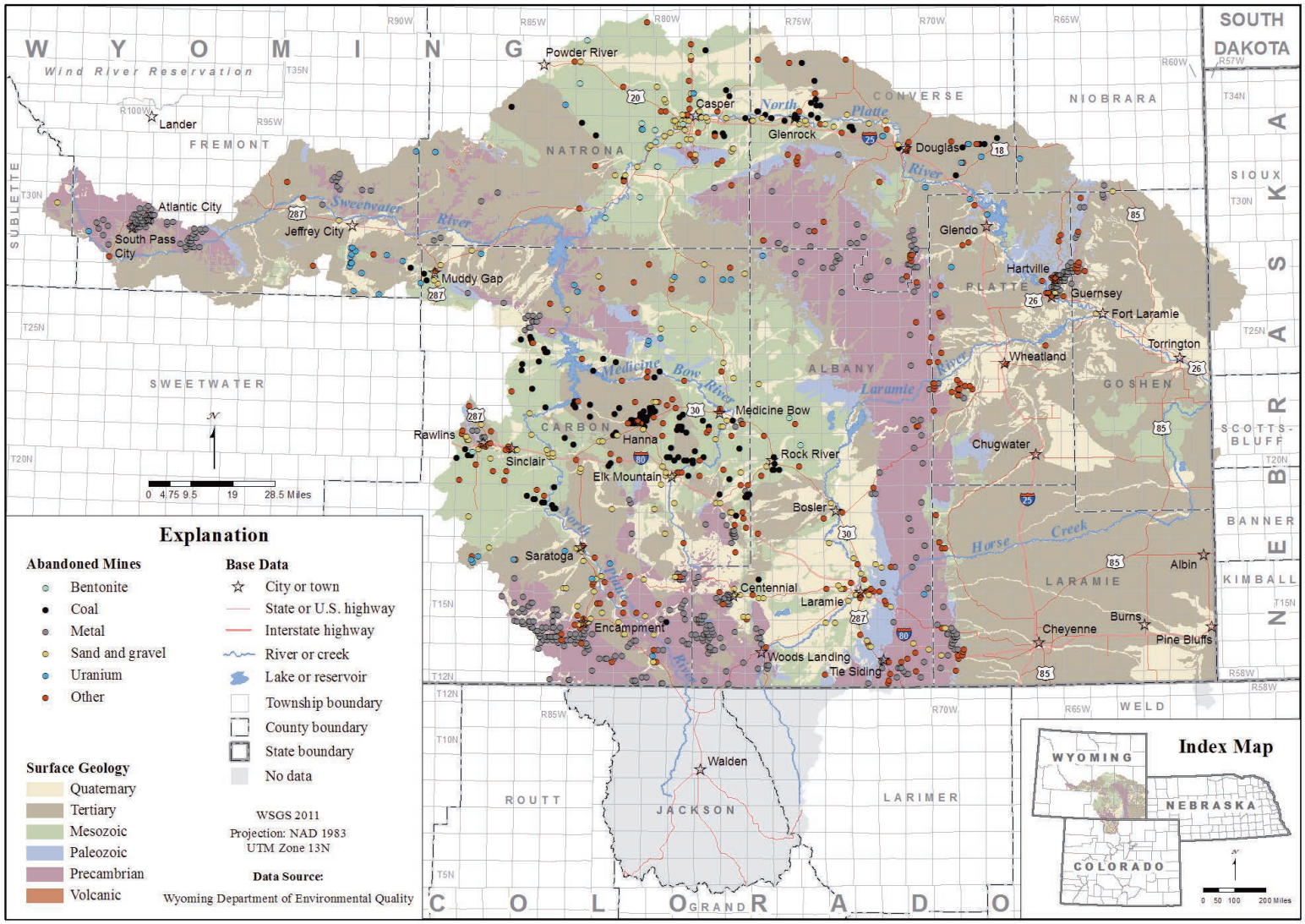


Figure 5-7. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality Abandoned Mine Land Division abandoned mine sites, Platte River Basin, Wyoming.

substantial volumes of other products that can pose a threat to groundwater such as fuel, methanol, glycols, amines, lubrication and hydraulic oils, acids, and a variety of well hydraulic fracturing and treatment chemicals. Large volumes of waste and wastewater are typically generated by oil and gas operations. Releases can occur from storage tanks, process vessels, and above-ground and underground piping. In some cases hydrocarbons, produced water, and other chemicals are discharged to pits constructed for a wide variety of applications. Older and abandoned pits were commonly unlined and; therefore, have greater potential for groundwater contamination. Notably, the historic storage and disposal of relatively mobile natural gas condensate in unlined pits has resulted in confirmed shallow groundwater contamination at several locations in the Platte River Basin. Prevention and mitigation of groundwater contamination resulting from releases of petroleum hydrocarbons is a primary area of concern and regulation by local, state, and federal agencies.

- **Pipelines:** Interstate and intrastate pipelines transport a variety of liquids that if released by rupture, malfunction, operational problems, or leaks can migrate to groundwater. Small leaks from buried pipelines can go undetected for extended periods of time and release substantial volumes of contaminants.
- **Active and permanently abandoned injector and disposal wells:** Injector wells are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources for disposal, for maintaining reservoir pressure for enhanced oil recovery, and other purposes. Injector wells are mapped as potential contaminant sources because there are several in the Platte River Basin and because they typically inject large volumes of produced water that could pollute groundwater resources if leaked into shallower aquifers. Injection facilities also employ bulk storage tanks, piping systems, and other equipment that can release produced water or other contaminants in recharge areas. Class II wells are strictly regulated by the WOGCC and the BLM/EPA and generally pose minimal potential for impacting groundwater resources by excursions from the injection interval; however, releases during surface operations or through poorly cemented well casing, though rare, are potential avenues of contamination. Class II injection wells are located within oil and gas fields.

Figure 5-5 – Potential groundwater contaminant sources: Class I and V injection wells in the WDEQ UIC Program, and active and expired outfalls in the WDEQ WYPDES program

- **Class I and V UIC injection wells:** Class I underground injection wells and Class V injection facilities are regulated through the WDEQ Underground Injection Control (UIC) Program. In Wyoming, Class I wells inject non-hazardous wastes (RCRA definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal makes up a large component of injected fluids. Class I wells are strictly regulated and generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they are allowed to accept for injection. In contrast, Class V facilities are used to inject a wide range of non-hazardous fluids generally above or directly into shallow aquifers and therefore have a substantial capacity for impacting groundwater resources. Many Class V wells in Wyoming are associated with groundwater contamination, and new injection of industrial wastes has been banned. Currently, only 3 Class V facilities, permitted to inject industrial

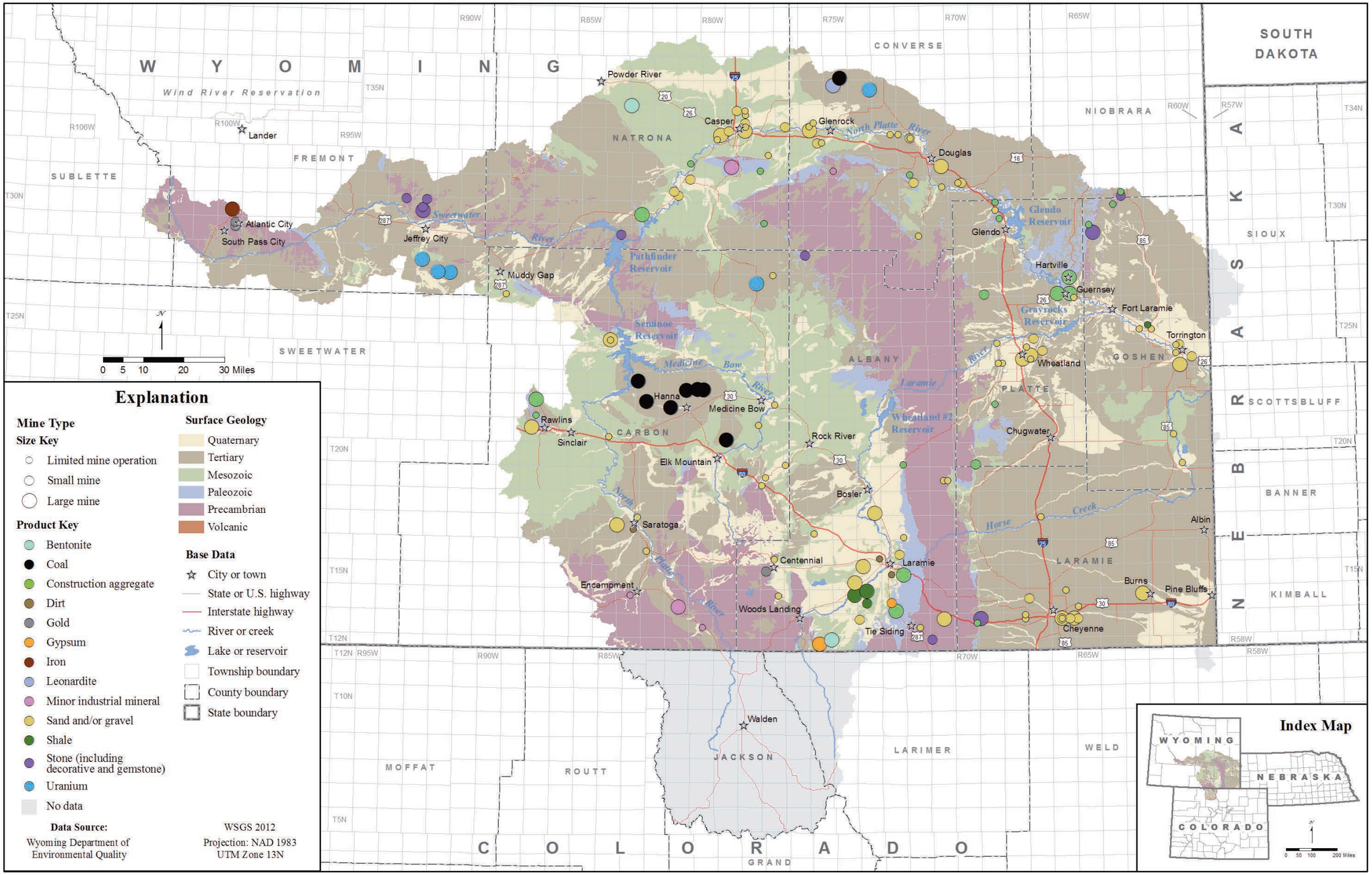


Figure 5-8. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality Land Quality Division permitted mines, {quarries, and pits}, Platte River Basin, Wyoming.

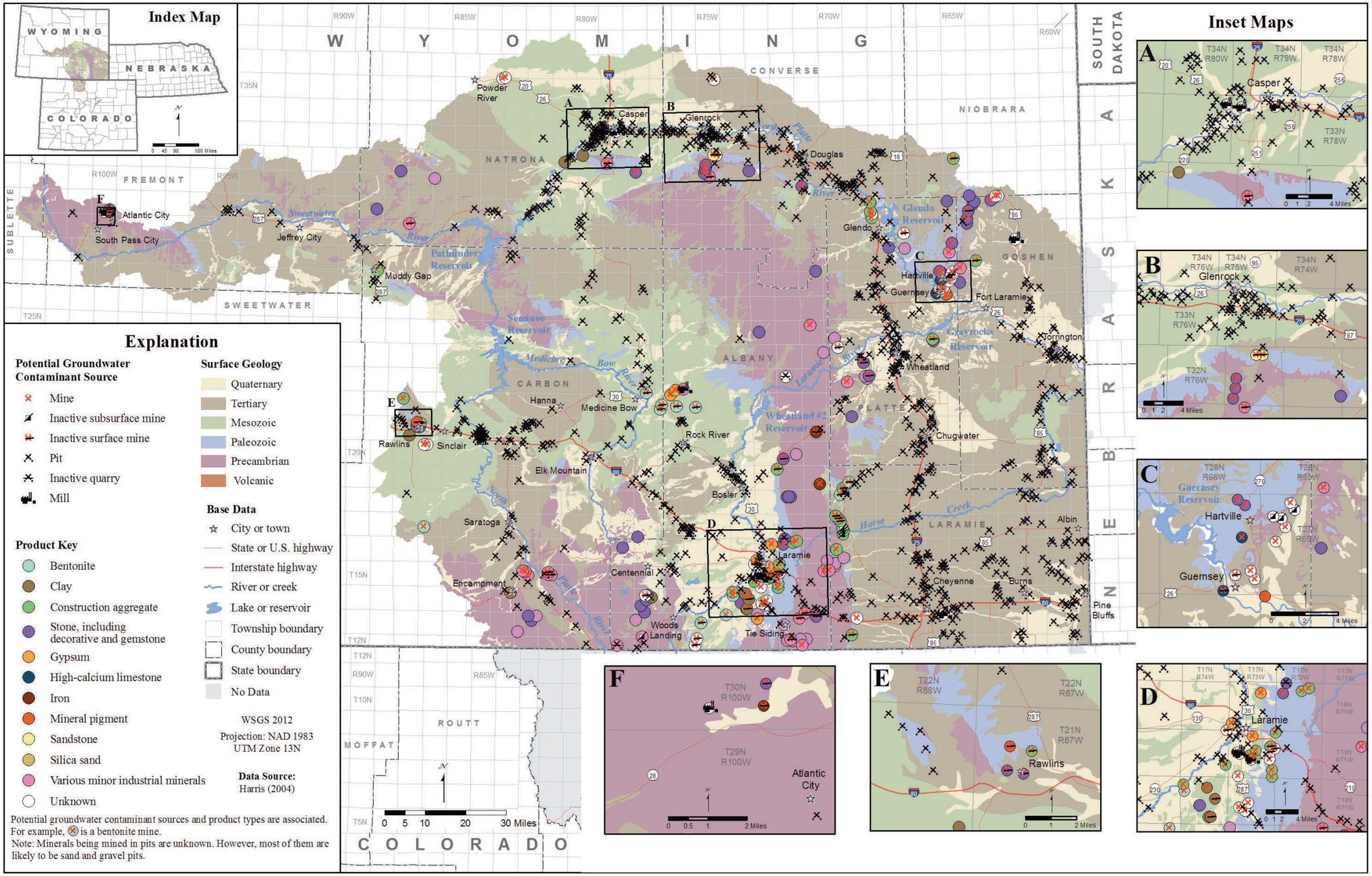


Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Platte River Basin, Wyoming, (locations from Harris, 2004).

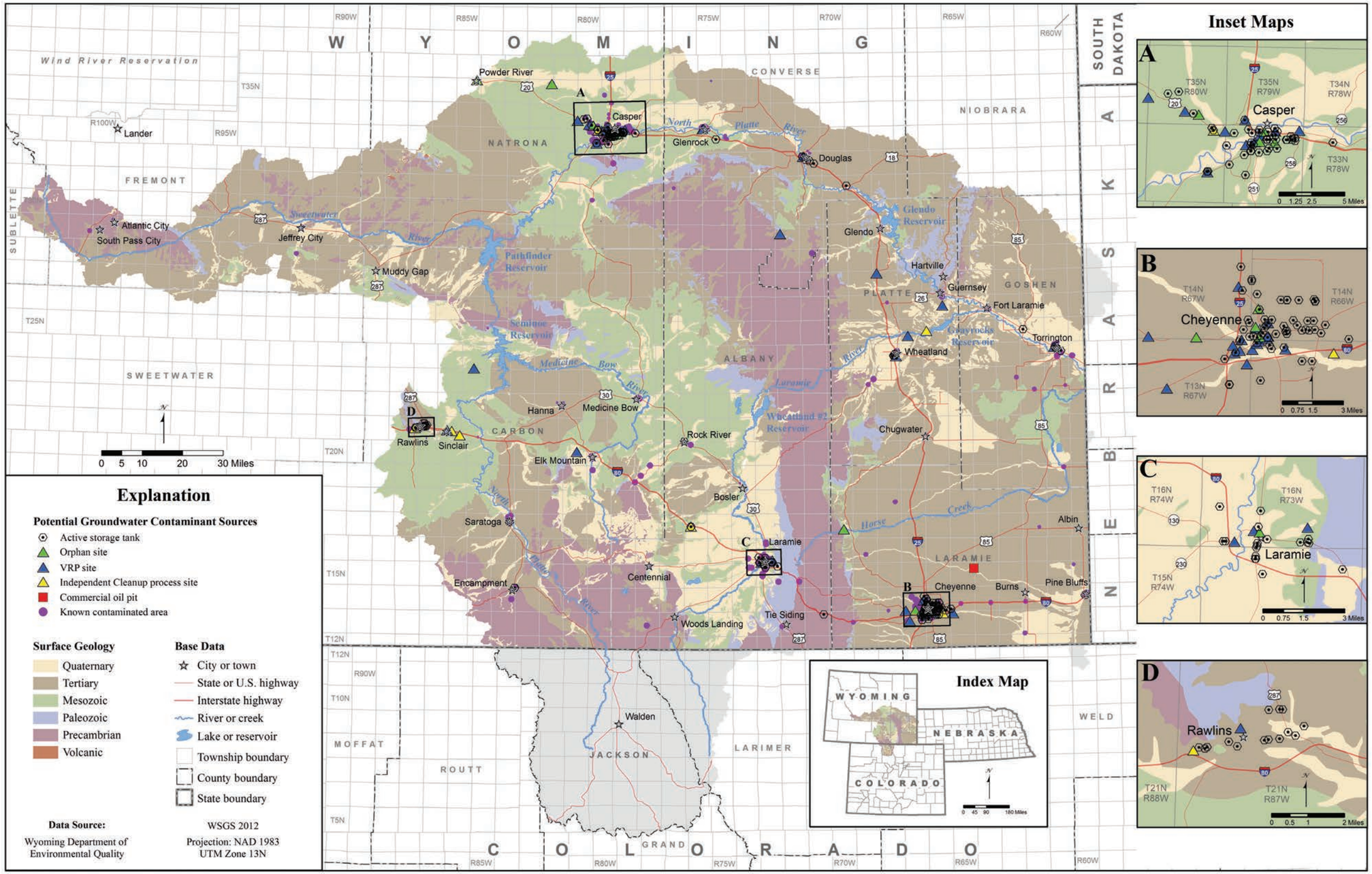


Figure 5-10. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality (WDEQ) permitted storage tanks and commercial disposal pits; WDEQ Voluntary Remediation Program (VRP), Brownfield, Independent cleanup process (ICP), and orphan sites; and known contaminated areas in WDEQ's groundwater program, Platte River Basin, Wyoming.

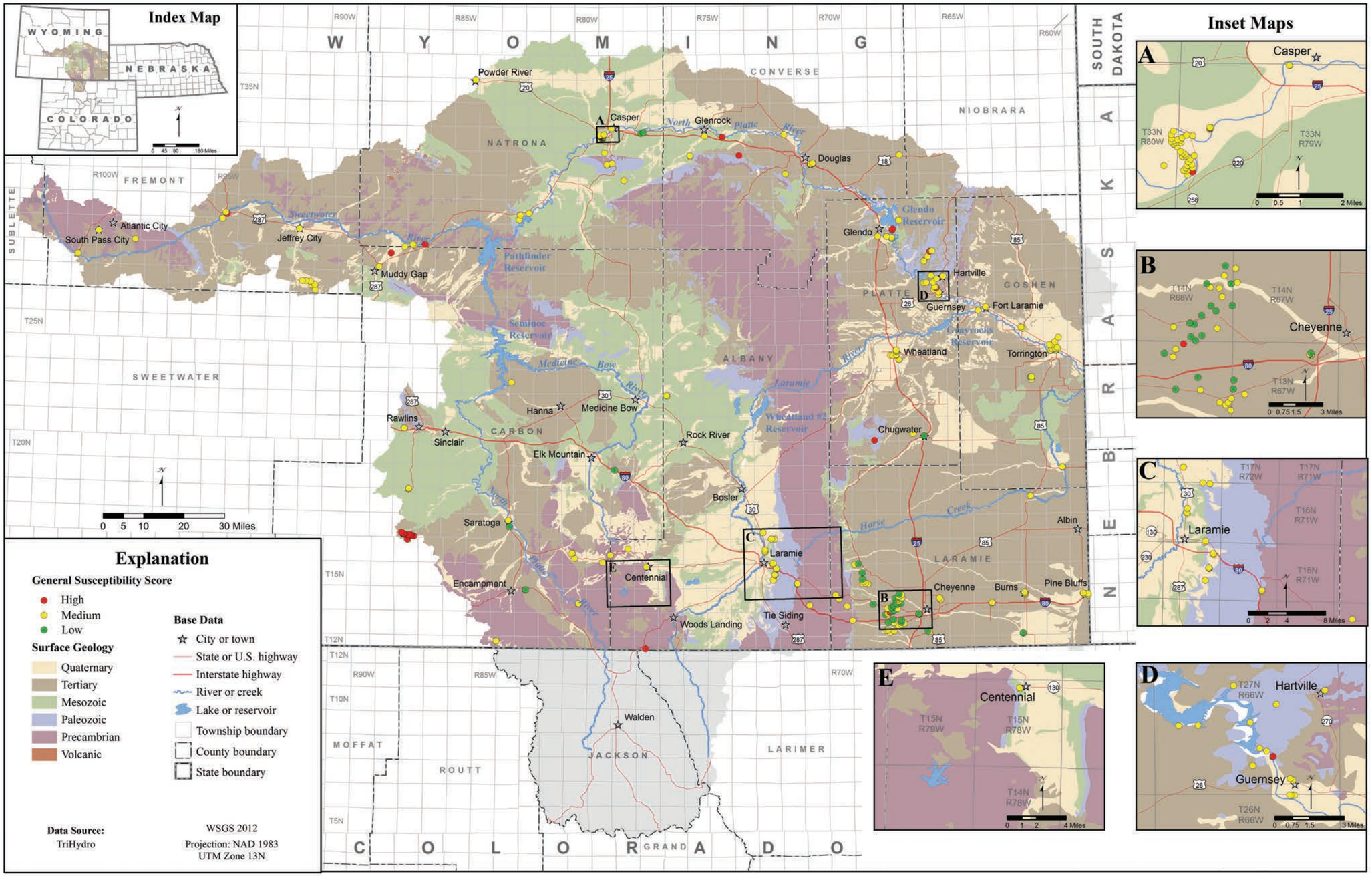


Figure 5-11. Surface Water Assessment and Protection, Platte River Basin, Wyoming.

wastes are operational in the state of Wyoming and these must follow stringent annual monitoring requirements. Some notable examples of Class V facilities are agricultural or storm water drainage wells, large-capacity septic systems, automotive and industrial waste disposal wells, and various types of infiltration galleries. Class I and Class V injection facilities also generally include bulk storage tanks, pipelines, and other equipment that could release contaminants in recharge areas.

- **Class III injection wells:** Class III underground injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells are used to inject fluids for in situ solution mining of various minerals (e.g., uranium, sulfur, copper, salts, trona, potash), for underground coal gasification, for the recovery of hydrocarbon gas and liquids from oil shale and tar sands, and for experimental/pilot scale technology applications. The largest concentration of Class III injection wells in the Platte River Basin is for in-situ uranium recovery located north of Glenrock, Wyoming near the northern margin of the drainage basin.
- **Active and expired WYPDES outfalls:** Discharge of any potential pollutant from a point source into surface waters of the state requires a WDEQ Wyoming Pollutant Discharge Elimination System (WYPDES) permit from the Water Quality Division (WQD). During flow to surface waters where contaminant concentrations may be diluted, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating shallow groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits and other impoundments are commonly installed along WYPDES flow paths to store water for other uses, and to slow flow rates to minimize erosion and remove sediment. These installations all enhance the amount of surface flow that can infiltrate into the subsurface by increasing the time and area over which discharged water is in contact with the stream channel or storage basin. WYPDES outfalls are associated with a variety of facilities in the Platte River Basin, several of which discharge produced water from oil and gas operations.

Figure 5-6 – Potential groundwater contaminant sources: WDEQ solid and hazardous waste facilities and concentrated animal feeding operations (CAFOs)

- **Solid and hazardous waste facilities -** Permitted by WDEQ Solid and Hazardous Waste Division (SHWD) including:
  - Municipal landfills, and transfer, treatment, and storage facilities.
  - Industrial landfills, treatment, and storage facilities.
  - Solid waste treatment, storage, and disposal facilities.
  - Spill and hazardous waste corrective action sites.
  - Illegal dump sites and historic site cleanups.

Solid and hazardous waste facilities contain a great number of potential contaminants in a variety of configurations. Wastes may be liquid, solid or semisolid forms, stored above- or below-ground in contained or uncontained repositories. Wastes are generally concentrated at these facilities, including concentrated liquid products that can leak from containers. Contaminants can migrate to groundwater in several ways. Contaminants can migrate directly to shallow groundwater, or water from precipitation and other sources can infiltrate contaminant sources above the water table and form leachates composed of many contaminants. Active facilities usually store bulk contaminant products on-site (e.g., fuel, hazardous materials for recycling) that can also be sources of contamination if released.

- **CAFOs:** Concentrated animal feeding operations are permitted by the SHWD. Outfalls from CAFOs are also permitted under the WYPDES Program. The

primary potential contaminant generated at CAFOs is animal waste. Other farm and ranch potential contaminant sources include stored bulk fuels, antifreeze, used oil, pesticides, and herbicides. Small "ranch dumps," and landfills may also be located near CAFOs.

Figure 5-7 – Potential groundwater contaminant sources: WDEQ storage tanks, commercial wastewater disposal pits, Volunteer Remediation Program (VRP) and Independent Cleanup Process (ICP) sites, brownfield sites, orphan sites, and Groundwater Program Known Contaminated Areas

- **Active storage tanks:** In use or temporarily out of use, above- and underground storage tanks are regulated by the WDEQ/SHWD Storage Tank Program. Because releases can go undetected for long periods of time, underground storage tanks (USTs) have long been recognized for their potential to contaminate groundwater. The Storage Tank Program was developed, in large part, in response to the high number of releases from USTs.
- **VRP and ICP Sites:** These are sites where soil or groundwater contamination is remediated by agreement between the SHWD and the responsible party under the Voluntary Remediation Program (VRP). By definition, sites enrolled in this program are associated with contaminated soil or groundwater or both.
- **Orphan and brownfield assistance sites:** These are contaminated sites where a viable responsible party other than the state does not exist (orphan), or sites with known or suspected contamination that are owned by local, state or federal government entities (brownfield).
- **Commercial wastewater disposal pits:** Commercial wastewater disposal pits are regulated by the WDEQ Water Quality Division (WQD) Water and Wastewater Program. These facilities deal primarily with produced water from oil and gas operations but can receive other wastes with prior approval of the WDEQ. Produced water disposed at these facilities is commonly accompanied by liquid hydrocarbons, which are generally recovered for sale. Releases can occur from operational malfunctions, underground leaks directly from pits, and leaks from pipes and storage tanks.
- **Known contaminated areas:** These sites are generally regulated by the WQD Groundwater Pollution Control Program. They include sites with confirmed soil and groundwater contamination that have not entered the VRP and are being addressed under orders from the WDEQ.

Figures 5-8 through **5-10** show the locations of active and abandoned mines, quarries, pits, and similar operations. These facilities and sites can impact groundwater in several ways. Stripping topsoil from an area increases infiltration rates and removes the capacity for biodegradation and retardation of contaminants within the soil horizon. Excavations can impound large quantities of water and enhance recharge or become hydraulically connected to the water table along with any contaminants. Exposure of metal-rich lithologies to the atmosphere can oxidize and mobilize dissolved concentrations. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) and wastes stored or generated can more quickly infiltrate to the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-8 – Potential groundwater contaminant sources: WDEQ Land Quality Division (LQD) permitted mines, quarries and pits

Three active mine types are regulated by the WDEQ Land Quality Division (LQD):

- **Active limited mining operations (LMO)** are exempt from the DEQ's full permitting process. LMOs are restricted to a maximum of 10 acres for the life of the mine.
- **Active small mines** may disturb up to 10 acres per year but do not have a limit on the total area disturbed.

- **Active large mines** have no limit on total disturbance area or on how many acres may be disturbed per year.
- **Active coal mines** mapped by the WSGS are also included in **Figure 5-8**.

Figure 5-9 – Potential groundwater contaminant sources: WDEQ/Abandoned Mine Land (AML) Program, abandoned mine sites - shows the location of abandoned mine sites inventoried and under the jurisdiction of the WDEQ AML Division. These include sites where reclamation may or may not have been completed.

Figure 5-10 – Potential groundwater contaminant sources: WSGS mapped mines, pits, mills, and plants - includes active, inactive, abandoned, and proposed facilities and sites, partially duplicating mine sites shown on **Figures 5-8** and **5-9.** However, because the data for **Figure 5-10** was compiled prior to and independently of the data compiled for **Figures 5-8** and **5-9**, it might provide a more comprehensive picture of mining locations in the Platte River Basin.

5.7.3 Discussion

To be included in this study, location data for potential contaminant sources had to be in formats that could be imported into ARC/GIS format. Some of the types of facilities listed below are not found in the Platte River Basin. Some contaminant source types do not currently have the location data in the ARC/GIS format required for mapping, or the data exist but were not available. The following types of potential groundwater contaminant sources were not mapped in this study:

- Although a large number of public owned treatment works (POTWs) and septic systems exist in the Platte River Basin, they were not mapped because adequate location data were not available. However, some large-capacity septic systems have been mapped as Class V injection facilities **(Figure 5-5)**.
- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the Platte River Basin Final Report (Trihydro Corporation and others, 2006a - Figures 2-7 through 2-13) shows the primary areas where agricultural chemicals would generally be applied in the Platte River Basin. In addition, recent USGS reports (Bartos and others, 2009; Eddy-Miller and others, 2013) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC (Hamerlinck and Arneson, 1998) report to be most vulnerable to this type of contamination. The application of pesticides and herbicides is regulated by the WDEQ Nonpoint Source Program.
- There are currently no underground coal gasification (UGC) sites in the Platte River Basin.
- Produced water pits regulated by the WOGCC, oil and gas field plants and compressor stations were not individually mapped for this study. These potential sources are located within the oil and gas fields mapped in **Figure 5-4.**
- Construction/demolition landfills, hazardous waste and used oil generators, used oil transporter and storage facilities, one-time disposal authorizations, mobile treatment units, *de minimus* spills, and complaints were included in the data received from WDEQ/SHWD but are not shown on **Figure 5-6** due to variable location (mobile) or relatively low potential for contaminating groundwater.

The above list and description of potential groundwater contaminant sources may be incomplete. This study may have overlooked additional potential sources associated with sufficient volumes of contaminants of concern. Pending identification of additional potential sources and improvements in data (particularly location information) for the potential sources that were identified but not mapped for this study, it may be possible to include them in the next update to the Platte River Basin Available Groundwater Determination, Technical Memorandum.

5.7.4 Source Water Assessment Program, Wyoming Water Quality Monitoring Strategy and Associated Groundwater Protection Programs

The federal government, under the Clean Water Act, recognized that states have primary responsibility for implementing programs to manage water quality. The primary objectives included under this broad responsibility are 1) establishing water quality standards, 2) monitoring and assessing the quality of their waters, and 3) developing and implementing cleanup plans for waters that do not meets standards. To meet the water quality monitoring objective, WDEQ, the USGS Wyoming Water Science Center and other agencies have developed a suite of cooperative and complementary groundwater assessment and monitoring programs:

- Source Water Assessment Program (SWAP)
- WDEQ Water Quality Monitoring Strategy, led to the development of the Statewide Ambient Groundwater Monitoring Program also known as the Wyoming Groundwater-Quality Monitoring Network
- The USGS Pesticide Monitoring Program in Wyoming

A general discussion of these programs follows. More information can be obtained from the DEQ WQD website at http://deq.state.wy.us/wqd/groundwater/index.asp under the Groundwater Assessment and Monitoring section.

The Source Water Assessment Program (SWAP)

The Source Water Assessment Program (SWAP), a component of the federal Safe Drinking Water Act enacted to help states protect both municipal and non-community public water systems (PWSs), provides additional information on potential local contaminant sources. The program, administered by the WDEQ Water Quality Division (WQD) and voluntary for the PWSs, includes the development of source-water assessments and protection plans, referred to as Wellhead Protection Plans (WHPs). The source-water assessment process includes: 1) determining the source-water contributing area, 2) generating an inventory of potential sources of contamination for each PWS, 3) determining the susceptibility of the PWS to identified potential contaminants, and 4) summarizing the information in a report. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming. Additional information on the SWAP in Wyoming can be accessed online at:

http://deq.state.wy.us/wqd/www/SWP%20WHP/SWAP%20FAQs.asp.

Copies of Source Water Assessment Reports for specific PWSs in the Platte River Basin can be accessed at: http://deq.state.wy.us/wqd/www/SWP%20WHP/index.asp.

Water Quality Monitoring Strategy

Wyoming's strategy to develop an ambient groundwater quality database and a monitoring and assessment plan is designed to "determine the extent of groundwater contamination, update control strategies and assess any needed changes in order to achieve groundwater protection goals" through a phased approach:

- Phase I – Aquifer prioritization (Bedessem and others, 2003; WyGISC, 2012)
- Phase II – Groundwater monitoring plan design (USGS 2011; USGS, variously dated)
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

Phase I – Aquifer prioritization

The aquifer prioritization process was a cooperative effort between the University of Wyoming, WDEQ, USGS Wyoming Water Science Center, Wyoming Geographic Information Science Center (WyGISC) and Wyoming State Geological Survey (WSGS) designed to develop a GIS based approach to determine critical areas within high use aquifers using available aquifer sensitivity (Hamerlinck and Arneson, 1998) and water and land use data. The goals of this process were to identify and rank the areas and aquifers that should be included in the statewide ambient

groundwater monitoring plan, and present the results in a series of maps. To do this, the project team included the following layers in the GIS model:

- Aquifer sensitivity map of Hamerlinck and Arneson (1998)
- High-use aquifers less than 500 feet below ground surface
- High-use aquifer sensitivity
- Current water use (domestic and municipal)
- Land use:
    - Coal bed methane wells
    - Rural residential development
    - Oil and gas exploration, development, and pipelines
    - Known and potential contaminant sources
    - Croplands and urban areas
    - Mining,
    - Composite land uses (up to six uses)

Based on these analyses, the Aquifer Prioritization Map distinguishes four relative priority categories within high-use aquifer/areas (Low, Low-Moderate, Moderate-High, and High). Bedessem and others (2003) contains complete descriptions of the methods used and subsequent results; the article is available online at the DEQ website: http://deq.state.wy.us/wqd/groundwater/downloads/NGWA%20Final.pdf. The map can be accessed online: http://deq.state.wy.us/wqd/groundwater/downloads/map11.pdf.

Phases II and III – Groundwater monitoring plan design, implementation and assessment

The groundwater monitoring plan was developed by the U.S. Geological Survey (USGS) and the Wyoming Department of Environmental Quality (DEQ) and instituted as the Wyoming Groundwater -Quality Monitoring Network (WGQMN). The program is designed to monitor wells located in the priority areas and completed in the high use aquifers susceptible to contamination identified in Phase I.

Data collection and reporting by the USGS/WDEQ include the following:

- Water level measurement.
- Water sample collection and analysis for numerous natural and manmade constituents.
- Stable isotope analysis in selected samples to determine the nature and extent of aquifer recharge.
- Public access online reporting of water level and chemical analysis data at: (http://waterdata.usgs.gov/ wy/nwis/qw/.
- Periodic publication of summary groundwater data in USGS Fact Sheets and Scientific Investigations Reports.

Program oversight is provided by a steering committee composed of representatives of the USGS, DEQ, U.S. Environmental Protection Agency (EPA), Wyoming Water Development Office, Wyoming State Geological Survey, and Wyoming State Engineer's Office. The steering committee meets periodically to evaluate program progress, and assess and modify program objectives.

Water quality analyses are conducted at the EPA Region 8 Laboratory in Denver, Colorado, and various USGS laboratories. A complete description of the program and priority areas can be found online: http://pubs.usgs.gov/fs/2011/3041/.

Phase IV – Education and outreach for local groundwater protection efforts

The DEQ/WQD Groundwater Section provides extensive educational material and website links on its Web page: http://deq.state.wy.us/wqd/groundwater/index.asp.

Information on specific Wyoming aquifers can be found online at the Water Resources Data System Library: http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html, and in the USGS Publications website: http://pubs.er.usgs.gov/.

USGS Pesticide Monitoring Program in Wyoming

The USGS initiated a groundwater sampling program in 1995 to develop a baseline water quality data set of pesticides in Wyoming aquifers. None of the 589 samples collected had pesticide levels exceeding the EPA Drinking Water Standards. The program is conducted in cooperation with DEQ and the Wyoming Department of Agriculture. Further program information and results are

available online in USGS reports: http://pubs.usgs.gov/sir/2009/5024/; http://pubs.usgs.gov/fs/2009/3006/ and http://pubs.er.usgs.gov/publication/fs20113011.

WDEQ Nonpoint Source Program

The goal of the Wyoming Nonpoint Source Program is to reduce the nonpoint source pollution to surface water and groundwater. The program directs efforts to reduce nonpoint source pollution, administers grants for pollution reduction efforts and aids in watershed planning efforts. A 13 member steering committee, appointed by the Governor, provides program oversight and recommends water quality improvement projects for grant funding. More information about this program can be obtained online: http://deq.state.wy.us/wqd/watershed/nps/NPS.htm.

All three programs address the common goal of to protect Wyoming's groundwater resources and inventory potential sources of contamination. The programs can be mutually beneficial by working together and including relevant information, either directly or by reference, to supplement their databases. Organizing as much groundwater quality and hydrogeologic information into an evolving master database would be useful in protecting and sustainably developing groundwater resources throughout Wyoming.

Chapter 6

Platte River Basin Hydrogeology and Groundwater Resources

Paul Taucher and Karl Taboga

Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. The hydrogeologic units in the Platte River Basin consist of saturated strata and fractured crystalline rocks that store and convey groundwater. These units range in geologic age from Quaternary to Precambrian (**Plates 1** and **2**) and are variably permeable. Generally, aquifers store and transport useable amounts of groundwater while less permeable confining units impede groundwater flow. In practice, the distinction between aquifers and confining units is not so clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all of the geologic units in the Platte River Basin, including confining units, are capable of yielding at least small quantities of groundwater to wells. For example, although the Mowry Shale and Niobrara Formation are classified as confining units throughout the Platte River Basin, several domestic supply and stock wells have been completed in these units (**Figures 8-6** and **8-15**), according to the records of the Wyoming State Engineer's Office (SEO). Permeability can vary widely within an individual geologic unit depending on the lithology in the unit and geologic structure present. For example, intergranular permeability in the unfractured limestone strata of the Casper aquifer is estimated to be only one hundredth to one thousandth of the measured permeabilities of the unit's sandstone members. In another case, the Precambrian formations commonly found in the mountainous regions of Wyoming generally function as confining units except near the surface where these formations have developed extensive sets of joints, cracks, and fractures as the result of tectonic uplifting and weathering. The great differences in permeability between geologic units account, in part, for the observed wide variation in the available quantity and quality of a basin's groundwater resources.

One of the primary purposes of this study is to evaluate the groundwater resource of the Platte River Basin through the following tasks (**Chapter 1**):

- Estimate the quantity of water in the aquifers.
- Describe the aquifer recharge areas.
- Estimate aquifer recharge rates.
- Estimate the "safe yield" potential for the aquifers.

Although an enormous quantity of groundwater is stored in the Platte River groundwater basin, the basin's complex geology does not permit the use of the general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties commonly employed by hydrogeologists in other settings that would be required to calculate a plausible estimate of total and producible groundwater resources. The data required for a basin-wide aquifer-specific assessment of groundwater resources is not available and is unlikely to ever be developed. Therefore, groundwater resources are evaluated in this study by using previous estimates of recharge (Hamerlinck, J.D. and Arneson, 1998) to the outcrop zones of the basin's identified aquifers (**Figures 6-1 through 6-6**) and the formulation of a basin-wide water balance (**Chapter 8**). The technical and conceptual issues concerning recharge are discussed in **Section 5.1.3**.

In theory, safe yield would be equal to the amount of recharge that exceeds the total discharge from an aquifer with groundwater in storage remaining essentially static or, stated another way, the amount of water that can be withdrawn from an aquifer without causing an unacceptable decline in the potentiometric surface. Lacking accurate data for either recharge or discharge it is difficult to evaluate safe yield. However, the total recharge estimated in this chapter can be used as an upper limit of safe yield for the Platte River Basin aquifers. Technical and conceptual issues concerning safe yield are discussed in **Section 5.1.4**.

6.1 Hydrostratigraphy and recharge to aquifer outcrop areas

The first step in recharge evaluation requires the identification of the specific aquifers and groups of aquifers to which the recharge calculations will be applied (**Figures 6-1** through **6-6**). Several previous groundwater resource studies **(Section 2.2)** have grouped the Platte River Basin's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units. The hydrostratigraphy developed for this study is based on previous regional assessments and is summarized in the **Plate 2** hydrogeology map**,** in the hydrostratigraphic charts in **Plates J, K, M, S, T, U, Figure 7-2**,

and in **Chapter 7**. The hydrostratigraphic charts provide a detailed description of the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007), and for the subregions defined in **Chapter 2**. **Appendix A** provides detailed descriptions of the geologic units used to develop the surface hydrogeology shown on **Plate 2**.

Section 5.2 discusses how the "map" units of Love and Christiansen (1985), previously compiled into a Geographic Information Systems (GIS) database by the U.S. Geological Survey and Wyoming State Geological Survey (WSGS) were used to develop **Plate 2**. Love and Christiansen (1985), however, were not able to distinguish all of the stratigraphic units present in Wyoming and the Platte River Basin due to the sheer size of the data set and cartographic limitations. Therefore, some geologic units were not mapped as individual hydrogeologic units but, instead, are shown on **Plate 2** as undifferentiated. To address this, the outcrops of hydrogeologic units assigned as aquifers or aquifer groups **(Plate 2)** were aggregated by geologic age **(Plate 2 – inset).** These aggregated aquifers, or *aquifer recharge zones,* were generated as GIS shapefiles that were used to calculate recharge volumes and rates:

- **Quaternary Aquifers (Figure 6-1)**
- **Lower Tertiary Aquifers (Figure 6-2)**
- **Upper Tertiary Aquifers (Figure 6-3)**
- **Mesozoic Aquifers (Figure 6-4)**
- **Paleozoic Aquifers (Figure 6-5)**
- **Precambrian Aquifer (Figure 6-6)**

6.2 Average annual recharge

Although the saturated geologic units in the groundwater basins function as reservoirs that store enormous volumes of groundwater, with the exception of unconfined aquifers (primarily Quaternary and Tertiary strata) only a small fraction of the groundwater in storage can be withdrawn for beneficial use while most will be retained within the porosity of the aquifers. If only the volume of producible water in storage is considered, it would clearly be a non-renewable resource. The amount of groundwater that can be sustainably withdrawn from a typical aquifer system is controlled by recharge and total discharge, especially as withdrawal approaches or exceeds recharge. Under natural conditions, a state of dynamic equilibrium exists in which natural discharge to surface waters are counterbalanced by recharge. If natural discharge and groundwater withdrawals approach or exceed recharge, springs, streams and wetlands will dry up, holders of surface water rights will not receive their appropriations and riparian ecosystems will collapse. This fact has long been recognized by ranchers and farmers and was incorporated into Wyoming's water law from its initiation.

The availability of estimated average annual recharge data from the Spatial Data and Visualization Center (SDVC) study (Hamerlinck and Arneson, 1998) and WSGS maps of the outcrop areas of the hydrogeologic units in the Platte River Basin (**Figure 5-2, Figures 6-1 through 6-6, Plate 2**) are used in this study to evaluate recharge on a regional scale. This section describes how the volume of average annual recharge within the Platte River groundwater basin was estimated.

Average annual recharge restrained by best estimates of annual discharge (both natural and by pumping) establishes a limit on how much development can be sustained without unacceptably depleting the groundwater held in storage, depleting natural discharges below acceptable levels, or causing permanent structural damage to an aquifer by irreversible compression of its rock matrix. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to estimate. Estimates of annual groundwater withdrawals and consumptive uses from the previous Platte River Basin Water Plan (Trihydro Corporation and others, 2006a) and Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007) are discussed later in this study (**Chapter 8**). Other analyses of Platte River Basin groundwater resources in **Chapter 8** include a basin-wide water balance, and analyses of recharge as a percentage of: 1) precipitation; 2) other water balance statistics; 3) estimates of current groundwater consumptive uses; and 4) estimated future groundwater requirements.

Estimated average annual recharge (**Figure 5-2)** in the Platte River Basin ranges from less than 1 inch per year in interior areas of the drainage sub-basins to 28 inches per year in the surrounding mountains (Hamerlinck and Arneson, 1998). Mountain and foothill areas receive higher

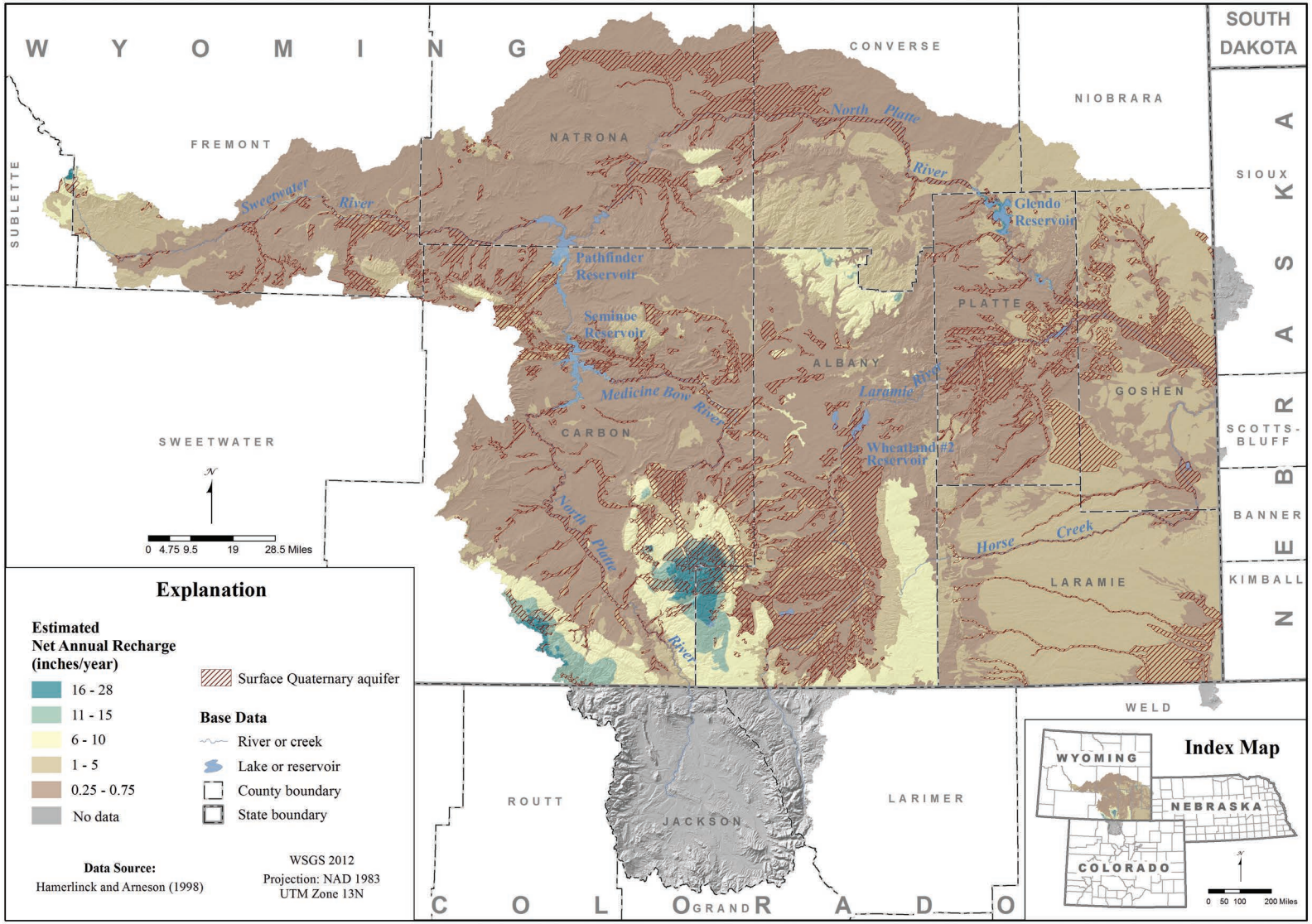


Figure 6-1. Estimated net annual aquifer recharge – surface **Quaternary** Aquifer, Platte River Basin, Wyomingg.

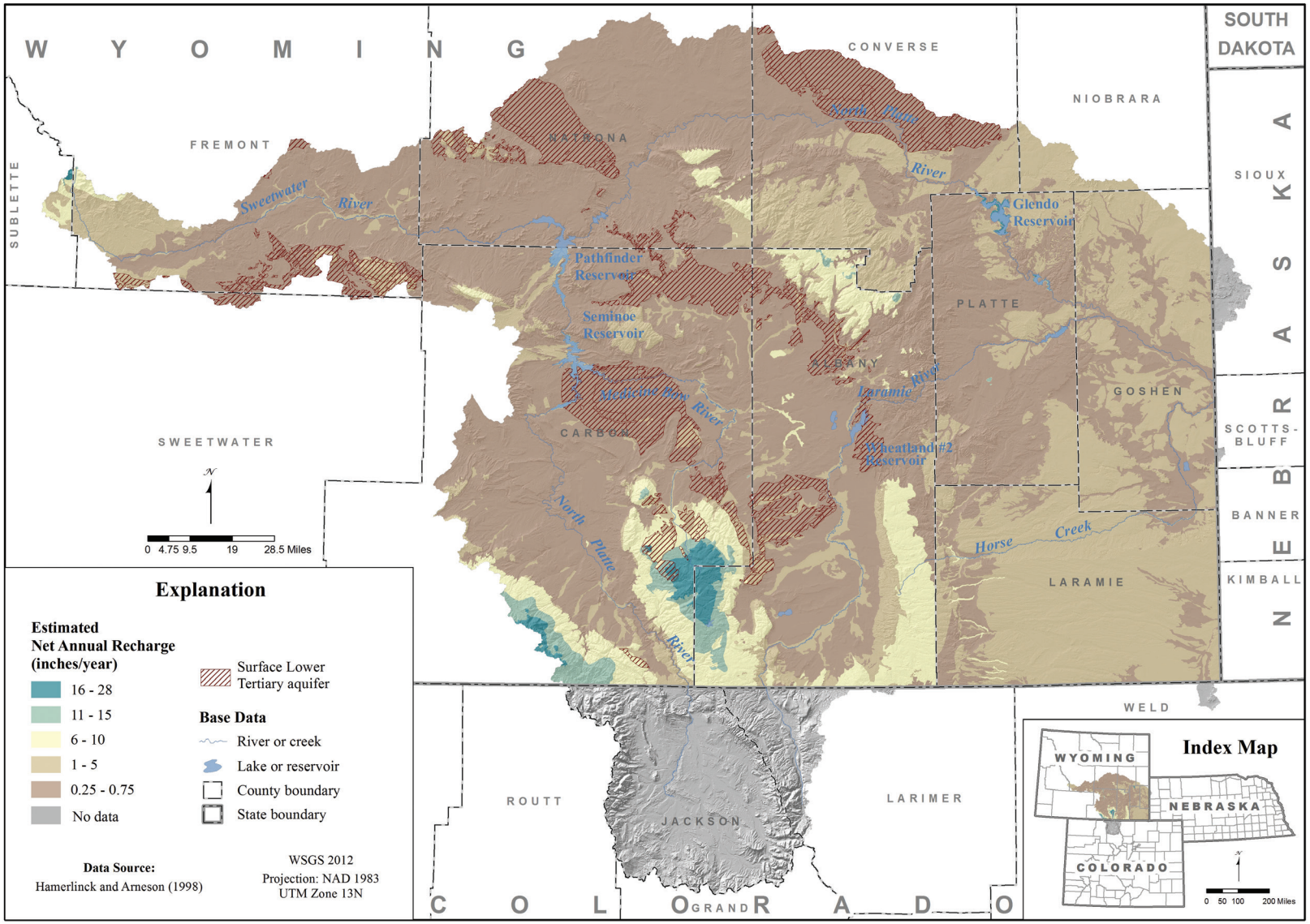


Figure 6-2. Estimated net annual aquifer recharge – surface **Lower Tertiary** Aquifer, Platte River Basin, Wyoming.

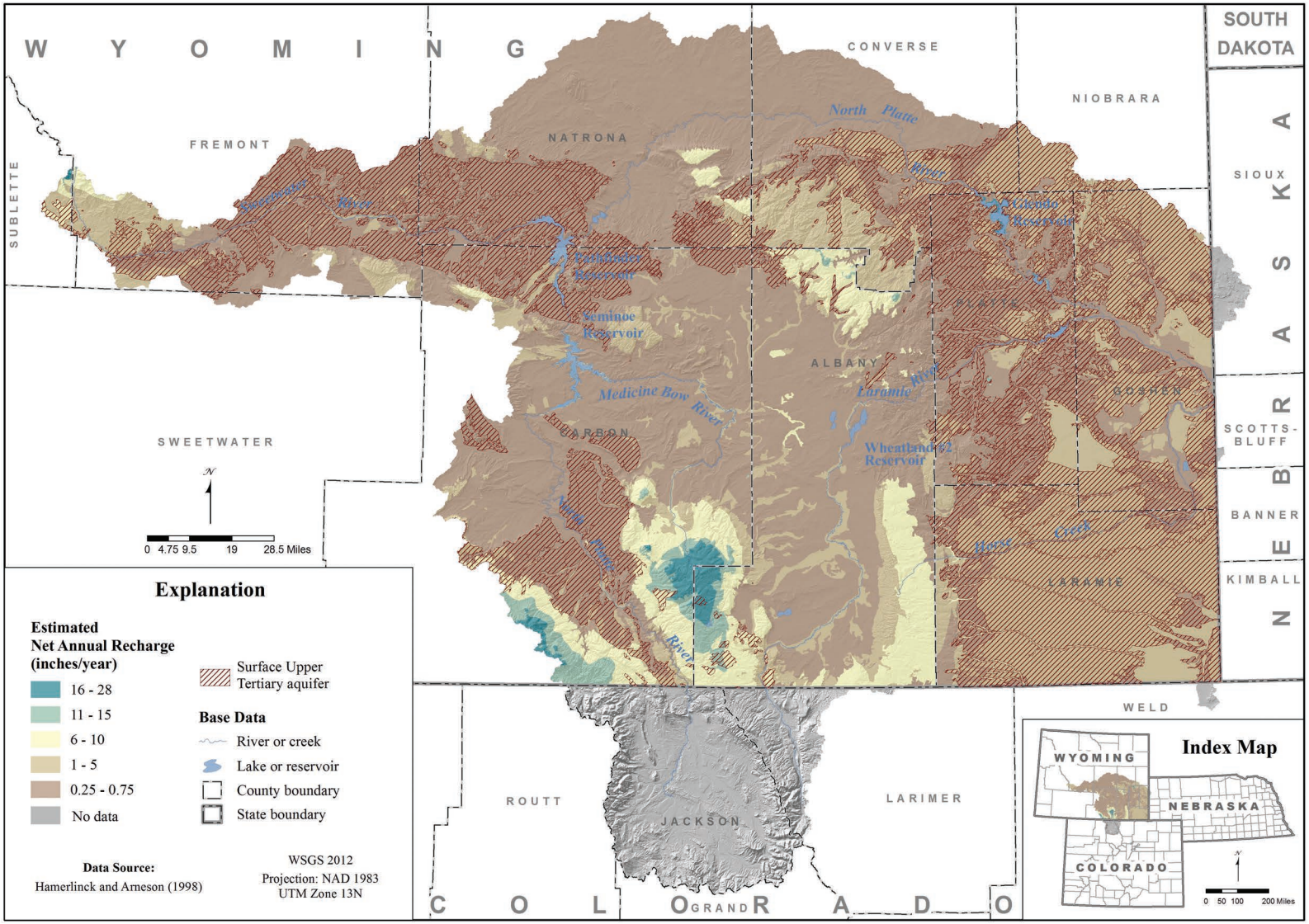


Figure 6-3. Estimated net annual aquifer recharge – surface **Upper Tertiary** Aquifer, Platte River Basin, Wyoming.

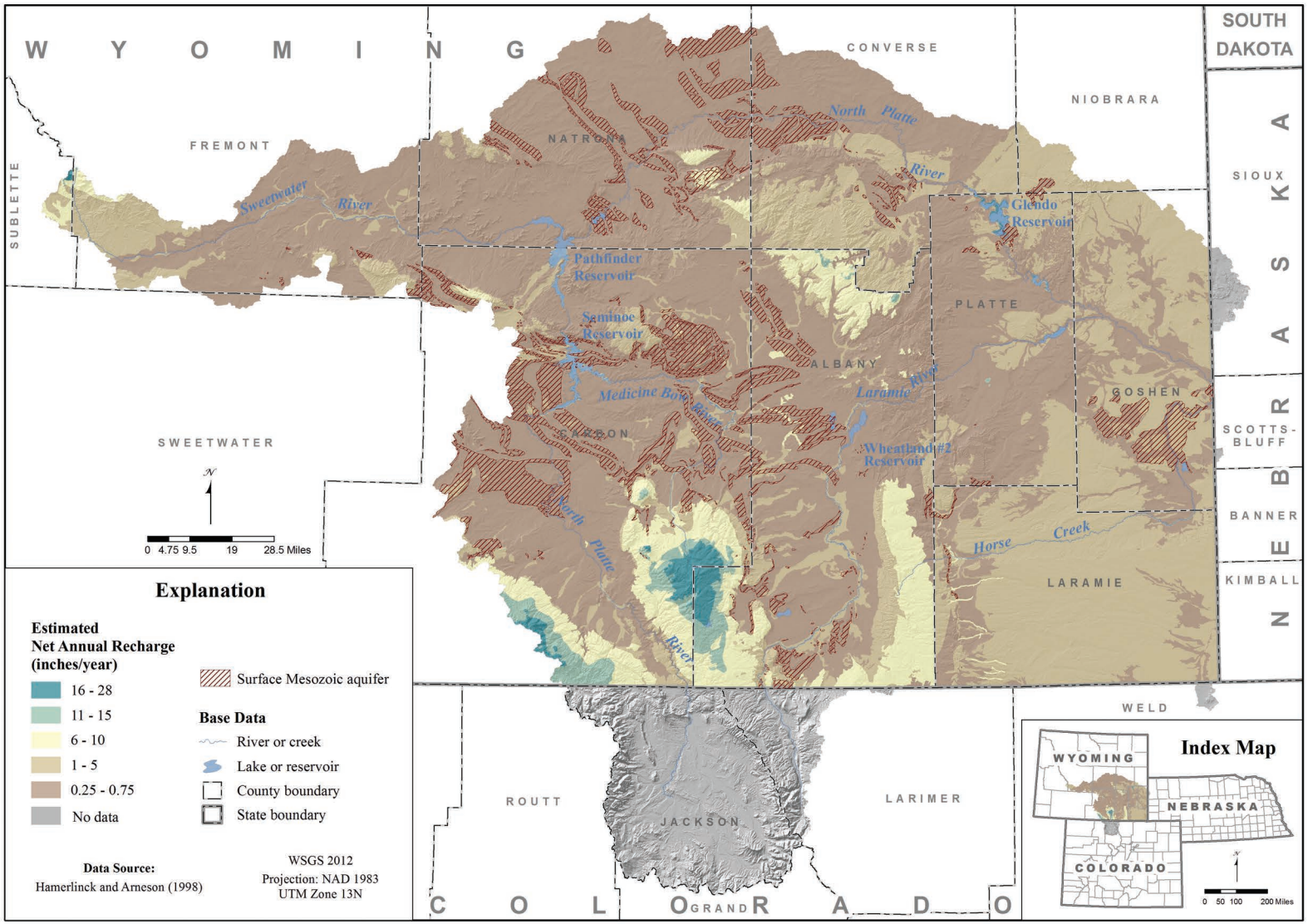


Figure 6-4. Estimated net annual aquifer recharge – surface **Mesozoic** Aquifer, Platte River Basin, Wyoming.

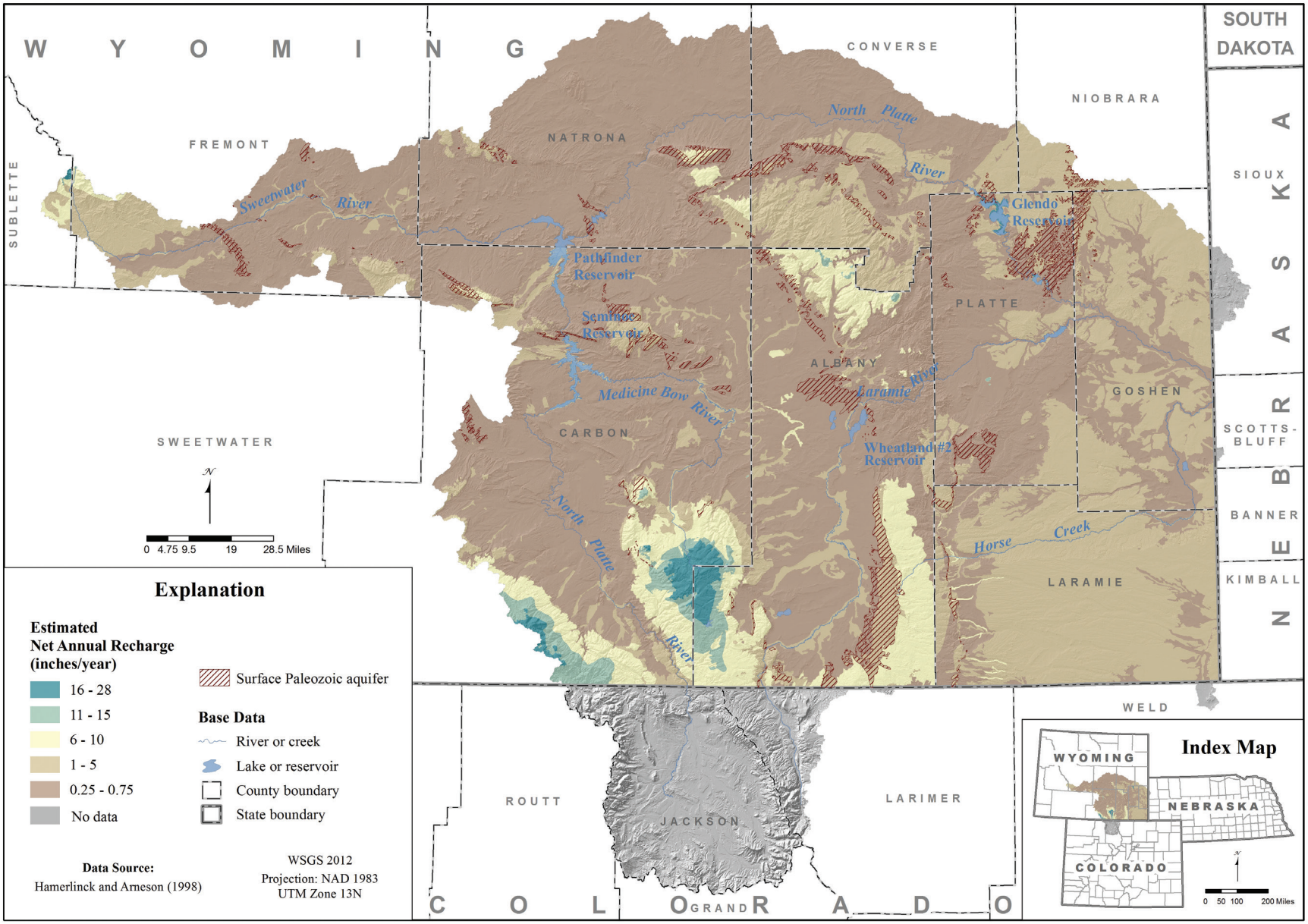


Figure 6-5. Estimated net annual aquifer recharge – surface **Paleozoic** Aquifer, Platte River Basin, Wyoming.

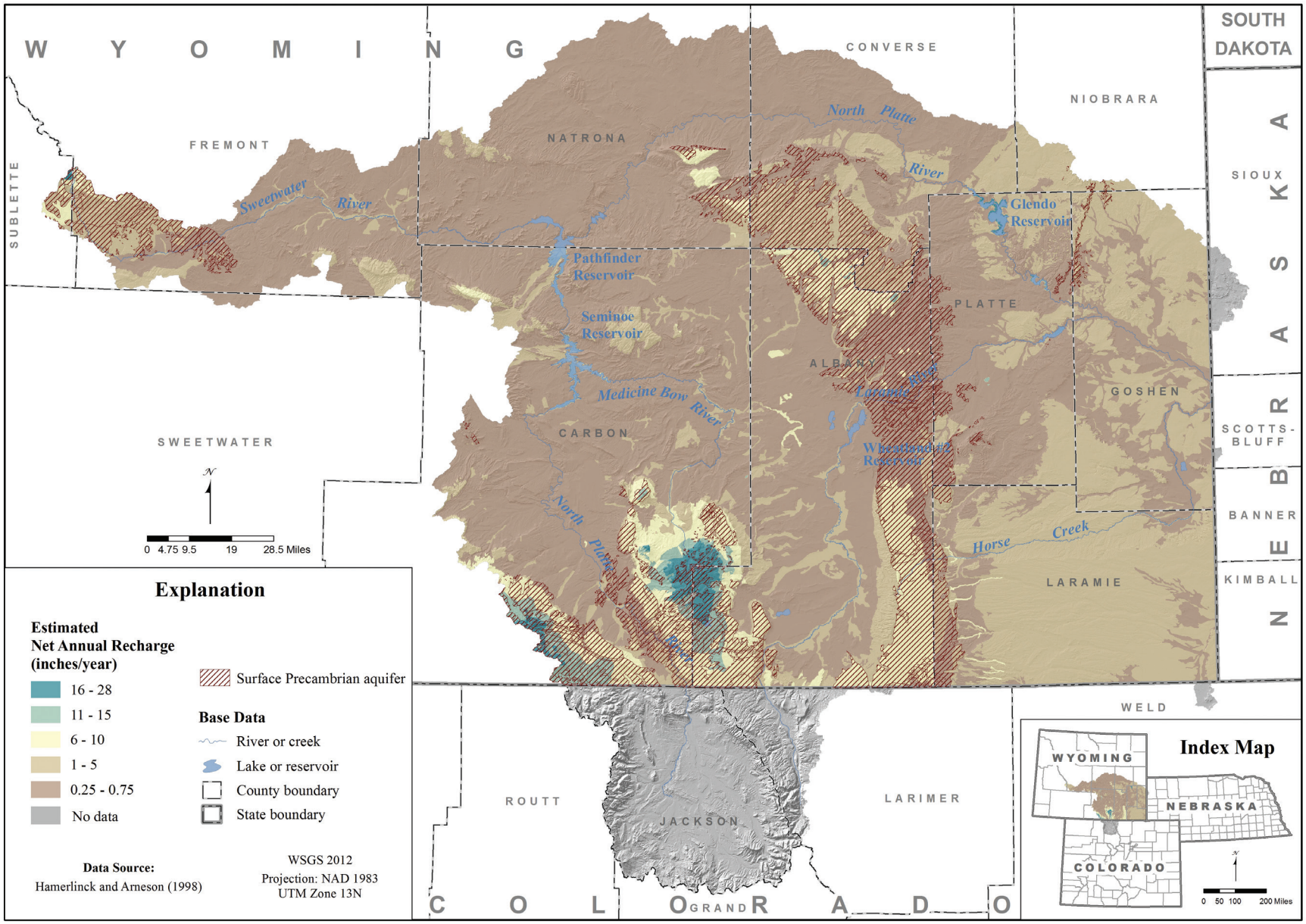


Figure 6-6. Estimated net annual aquifer recharge – surface **Precambrian** Aquifer, Platte River Basin, Wyoming.

amounts of recharge than basin lowlands due to environmental attributes characteristic of highland zones:

- Greater amounts of precipitation and more persistent snow pack.
- More abundant vegetation.
- Soil and vegetation combinations that are more favorable to infiltration.
- Lower rates of evapotranspiration.
- Better exposure of the upturned and weathered edges of hydrogeologic units along upland basin margins and associated greater permeability parallel to bedding.
- The presence of geologic structural features that enhance recharge (e.g., faults, fractures, joints, fault/fracture-controlled surface drainages).

Figure 6-7 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Platte River Basin and suggests what environmental factors exert control on recharge. Recharge takes place most efficiently in the mountain and highland areas, but recharge rates are also elevated around the Platte River's large reservoirs, in the outcrops of Paleozoic formations located south of Casper, Glenrock, and Douglas and in the outcrops of the High Plains Aquifer in the eastern part of the basin. The data set for **Figure 6-7** was generated by dividing 4,000-meter grid cells of average annual aquifer recharge shown in **Figure 5-2** (Hamerlinck and Arneson, 1998) by average annual precipitation (**Figure 3-3**) for the 30 year period of record from 1992-2010 (PRISM Climate Group, 2012). The average annual recharge rates depicted in **Figure 5-2** are based on percolation percentages for different soil/vegetation combinations. (Note that the PRISM data for the two 30 year periods of record (1961-1990 and 1992-2010) indicate that the precipitation volumes for the two periods are essentially equivalent as discussed in **Section 5.1.3.1**). Although this approach does not take into consideration all of the factors that affect recharge, initial infiltration and precipitation levels are probably the most important factors in a regional sense. Consideration of the other factors listed above and in **Section 5.1.3.1** should confirm the general pattern of recharge efficiency displayed in **Figure 6-7**. As discussed previously (**Sections 5.1.3.1 and 5.4**), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability).

Hamerlinck and Arneson (1998) indicated that most areas in the basin interior receive zero or, in some cases, negative amounts of recharge. This contradicts well-documented observations of the presence of shallow groundwater in both alluvial and bedrock aquifers throughout the subbasin interior lowlands of the Platte River Basin. In the absence of any recharge, the presence of shallow groundwater could not be sustained in these regions. So, during the development of **Figure 6-7**, minimal positive annual recharge values were assigned to lowland areas where Hamerlinck and Arneson, (1998) indicated that recharge is less than or equal to zero. A conservative low range of recharge (0.25 to 0.75 inches) was used for volume calculations and for developing **Figure 5-2** and the average of that range (0.5 inches) was used for developing **Figure 6-7**. This adjustment, while reasonable, does exert an influence on the appearance of both the recharge (**Figure 5-2)** and recharge efficiency maps (**Figure 6-7** and **Tables 6-1** through**6-3)**.

Table 6-1 shows the percent of surface area by specified range of recharge efficiency, as R/P, for each of the six age-classified *aquifer recharge zones* (**Plate 2 – inset, *Figures 6-1 through 6-6)***. Calculations were made by GIS analysis. These *aquifer recharge zones* are also used to calculate recharge volumes in **Chapter 8**.

Table 6-1 shows that most recharge to all *aquifer recharge zones* in the Platte River Basin occurs at the lowest range of recharge efficiency (2 percent to 10 percent of precipitation). Higher proportions of Paleozoic and Precambrian aquifers receive recharge at efficiencies greater than 10 percent than do younger units. This is likely due to the higher elevation exposures of older aquifers in upland areas where recharge is delivered more efficiently. The consistent low recharge efficiencies seen in the Tertiary and Mesozoic aquifer zones may reflect the relatively low variation in elevation and associated precipitation (**Figure 3-3**) in the subbasin interiors of the Platte River Basin. Areas of slightly higher recharge in the

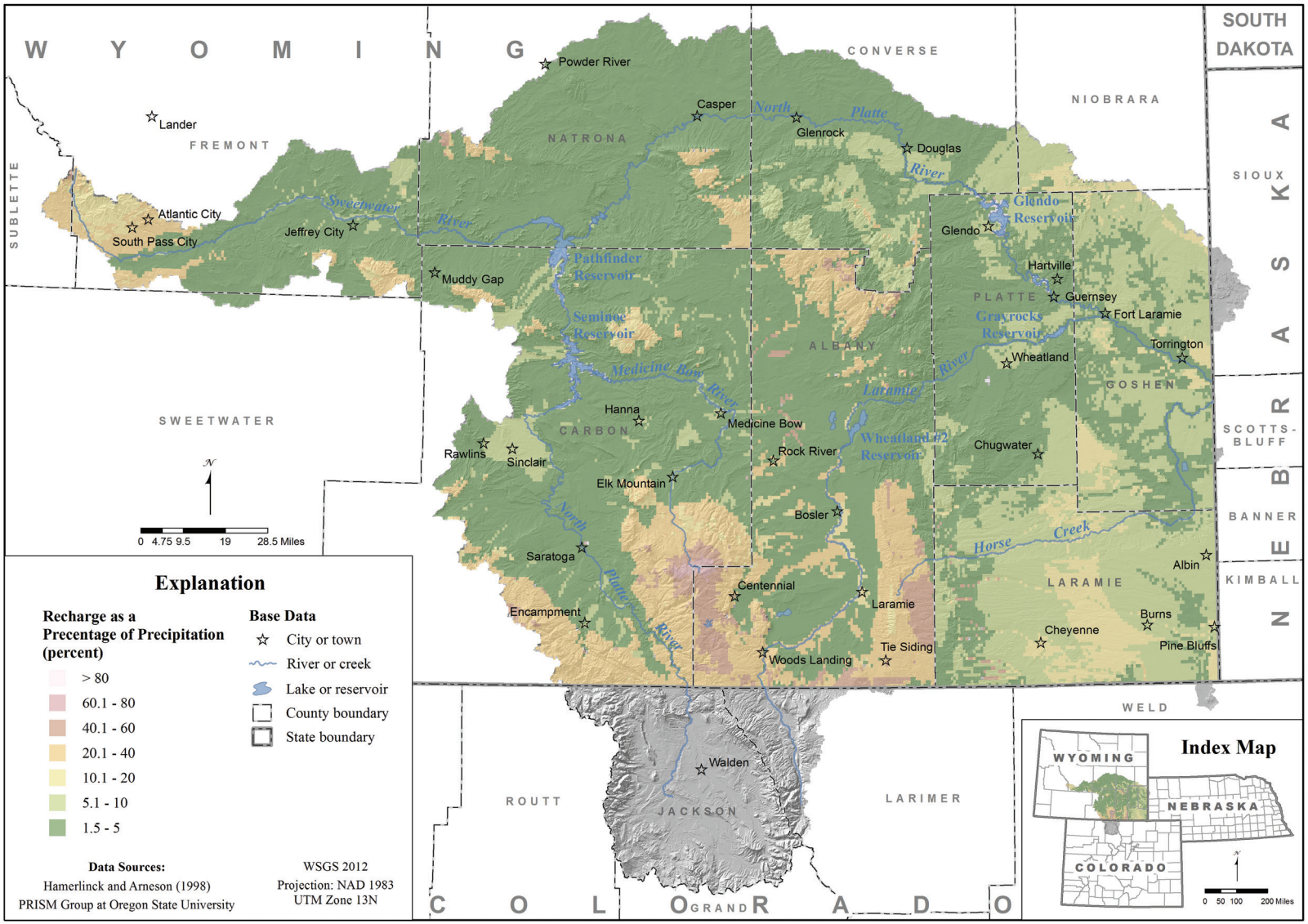


Figure 6-7. Aquifer recharge as percentage of precipitation using 1981 – 2010 precipitation normals, Platte River Basin, Wyoming.

Table 6-1. Platte River Basin Aquifers and Groups of Aquifers.

Percent of aquifer recharge zones recharging at varying efficiencies									
Recharge Efficiency as Annual Recharge / Annual Precipitation, in percent	2-10	11-20	21-30	31-40	41-50	51-60	61-70	71-100	>100
Quaternary	81.1	6.2	6.6	3.1	1.4	1.0	0.38	0.23	0.08
Upper Tertiary	89.2	8.3	1.2	0.67	0.34	0.06	---	---	0.16
Lower Tertiary	89.2	2.4	5.3	1.4	0.79	0.36	---	0.56	---
Mesozoic	92.7	1.2	3.7	1.1	1.0	0.19	---	0.22	0.01
Paleozoic	69.2	13.2	11.0	5.4	0.68	0.20	---	---	0.24
Precambrian	69.2	13.2	11.0	5.4	0.68	0.20	---	---	0.24

High Plains aquifer in eastern part of the basin may be due to more favorable soil/vegetation conditions. **Figure 6-7** also shows that elevated recharge efficiencies in excess of 80 percent are limited to those areas bordering the Seminoe, Pathfinder, and Glendo reservoirs. **S**ome of these areas have apparent recharge efficiencies above 100 percent.

Recharge volumes for the established *aquifer recharge areas* were calculated using the following general equation:
Average annual recharge volume (acre-feet) = ***Aquifer recharge area*** (acres) × Average annual recharge (feet)

The outcrop areas of the exposed aquifer groups used in the recharge calculations **(Figures 6-1 through 6-6)** were determined from the hydrogeologic map **(Plate 2)** developed for this study. As discussed above, average annual rates of recharge throughout the Platte River Basin (mapped in 100-meter cells), adapted from the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) are shown in **Figure 5-2**. Recharge rates were grouped into the five ranges to make **Figure 5-2** more readable, and to mitigate the uncertainties associated with the recharge calculations. Recharge rates for the *aquifer recharge zones*, mapped as polygons, were converted from inches to feet, and the average annual recharge volumes (in acre-feet) were calculated using the equation above.

With the exception of the Precambrian aquifer group, these recharge calculations do not consider confining unit outcrop areas (**Plate 2**). Although Precambrian hydrogeologic units are generally classified as confining, the Precambrian group was included as an aquifer because it provides useable amounts of groundwater in outcrop areas as a result of the formation of shallow secondary permeability from fracturing and weathering. As noted in **Section 5.2,** undifferentiated geologic units were included in the established *aquifer recharge areas* of the same era. Recharge calculations that exclude confining-unit outcrop areas provide a more conservative and probably more realistic estimate of available groundwater resources. Leakage from adjacent confining layers was not considered in this evaluation.

Table 6-2 summarizes calculated recharge for the Platte River Basin over the ranges of average annual recharge mapped on **Figure 5-2** and the *aquifer recharge zones* on **Figures 6-1 through 6-6.** Low and high recharge values were calculated by multiplying the surface area of each aquifer recharge zone by the lowest and highest recharge rate observed for each group. A "best total" amount for each range of recharge over the outcrop area of each aquifer group is also provided in **Tables 6-2** and **6-3** based on the recharge area for each integral inch of recharge in the database

Table 6-2. Platte River Basin Average Annual Recharge Calculations.

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	Acre-feet	Best Total (Acre-feet)
Quaternary	0.25	0.02	1,561,546	32,532	65,064
	0.75	0.06		97,597	
	1	0.08	614,963	51,247	85,728
	5	0.42		256,235	
	6	0.50	87,854	43,927	54,450
	10	0.83		73,212	
	11	0.92	48,861	44,789	52,127
	15	1.25		61,077	
	16	1.33	42,048	56,064	73,173
	28	2.33		98,112	
Low TOTAL			2,355,272	228,560	330,542
High TOTAL				586,231	

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	acre-feet	Best Total (acre-feet)
Mesozoic	0.25	0.02	1,073,053	22,355	44,711
	0.75	0.06		67,066	
	1	0.08	112,934	9,411	19,555
	5	0.42		47,056	
	6	0.50	13,627	6,813	8,359
	10	0.83		11,356	
	11	0.92	592	542	580
	15	1.25		739	
	16	1.33	442	589	873
	28	2.33		1,031	
Low TOTAL			1,200,647	39,711	74,077
High TOTAL				127,248	

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	acre-feet	Best Total (acre-feet)
Upper Tertiary	0.25	0.02	3,125,337	65,111	130,222
	0.75	0.06		195,334	
	1	0.08	2,562,974	213,581	268,817
	5	0.42		1,067,906	
	6	0.50	53,554	26,777	31,122
	10	0.83		44,628	
	11	0.92	7,452	6,831	7,224
	15	1.25		9,315	
	16	1.33	3,852	5,136	5,644
	28	2.33		8,988	
Low TOTAL			5,753,169	317,436	443,029
High TOTAL				1,326,171	

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	acre-feet	Best Total (acre-feet)
Paleozoic	0.25	0.02	259,420	5,405	10,809
	0.75	0.06		16,214	
	1	0.08	178,378	14,865	51,450
	5	0.42		74,324	
	6	0.50	19,302	9,651	11,170
	10	0.83		16,085	
	11	0.92	445	408	469
	15	1.25		556	
	16	1.33	296	395	499
	28	2.33		691	
Low TOTAL			457,841	30,723	74,397
High TOTAL				107,870	

ERA	Range of Average		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	acre-feet	Best Total
Lower	0.25	0.02	1,259,709	26,244	52,488
	0.75	0.06		78,732	
	1	0.08	121,767	10,147	33,180
	5	0.42		50,736	
	6	0.50	32,889	16,444	20,724
	10	0.83		27,407	
	11	0.92	6,655	6,100	6,640
	15	1.25		8,318	
	16	1.33	4,980	6,641	9,573
	28	2.33		11,621	
Low TOTAL			1,425,999	65,576	122,606
High TOTAL				176,814	

ERA	Range of Average		Outcrop Area Receiving Recharge	Range - Average Annual Recharge	
	Inches	Feet	Acres	acre-feet	Best Total
Precambrian (+ Qt & Tert)	0.25	0.02	710,375	14,799	29,599
	0.75	0.06		44,398	
	1	0.08	609,478	50,790	126,470
	5	0.42		253,949	
	6	0.50	731,226	365,613	461,534
	10	0.83		609,355	
	11	0.92	141,798	129,982	148,784
	15	1.25		177,248	
	16	1.33	60,381	80,507	105,995
	28	2.33		140,888	
Low TOTAL			2,253,259	641,691	872,382
High TOTAL				1,225,839	

Platte River Basin TOTAL	13,446,188	1,323,698 / 3,550,173	1,917,033

Conversion Factors:

$1ft^3$ =	7.480519	gal
1 acre-ft =	325,829	gal
$1m^2$ =	10.76391	ft^2

compiled for this study. Although these values fall between the high and low results, the "best total" is not an average of the high and low values but rather a "weighted average" calculated directly from the detailed (cell-by-cell) recharge data and the corresponding surface area.

Table 6-3 summarizes calculated average annual recharge statistics for the Platte River Basin from the more detailed calculations provided in **Table 6-2** and provides a "best total" average recharge depth. This last statistic, equivalent to the depth of recharge that would be delivered over the entire surface area of each aquifer recharge zone, provides a measure of recharge that is independent of surface area. An analysis of the values of "best total" average recharge depths shows that high elevation Precambrian aquifers collect four times the depth of recharge received by the basinward Tertiary and Mesozoic zones. Paleozoic aquifers, typically located in upland settings, and predominantly alluvial Quaternary age aquifers receive twice the depth of recharge as the basin aquifers.

Table 6-2 illustrates that, predictably, the percentages of recharge volumes are generally consistent with the surface areas of the *aquifer recharge zones.* However, while the *Upper Tertiary Aquifers* (**Figure 6-3**) constitute the largest *aquifer recharge area* in the Platte River Basin, they receive the second largest volume of recharge. The *Precambrian Aquifer* (**Figure 6-6**) with less than half the outcrop area of the *Upper Tertiary Aquifers* stands out as receiving more recharge than any of the other *aquifer recharge areas* (34 percent to 49 percent of all annual recharge). The *Quaternary Aquifers* (**Figure 6-1**) receive the third most recharge in the Platte River Basin. Although the *Paleozoic Aquifers* (**Figure 6-5**) are a very important source of groundwater, especially in the Laramie Basin, they constitute by far the smallest *aquifer recharge area* and receive the smallest recharge volume in the Platte River Basin.

For the most part, the high rates of recharge over the mountainous Precambrian outcrop areas do not translate into large quantities of stored groundwater. The hydrogeology of the Precambrian aquifers differs markedly from the sedimentary aquifers that overlie the crystalline basement rocks along the margins of uplifted areas and in structurally downwarped areas of the Platte River Basin. With low intercrystalline permeability the Precambrian basement complex in Wyoming typically functions as a confining unit except where it is exposed in uplifted areas and extensive joints, fractures and faults have developed as the result of tectonic activity and weathering. Groundwater is stored and transported through the "secondary porosity" formed by these shallow fractures, typically to depths of less than 300 feet below the lowest elevation of erosion along drainages. Aquifers dominated by secondary porosity are characterized by low storage and rapid transport times in contrast to the high storage coefficients but longer flow times exhibited by sedimentary aquifers with higher intergranular

Table 6-3. Annual recharge statistics[1] for Platte River Basin aquifer recharge zones.

Aquifer Recharge Zone	Recharge zone surface area (acres)	Percent of total basin surface area	Range - Average annual recharge (acre-feet)		"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth (feet)
			Low	High			
Quaternary	2,355,272	17.52%	228,560	586,231	330,542	17.24%	0.140
Upper Tertiary	5,753,169	42.79%	317,436	1,326,171	443,029	23.11%	0.077
Lower Tertiary	1,425,999	10.61%	65,576	176,814	122,606	6.40%	0.086
Mesozoic	1,200,647	8.93%	39,711	127,248	74,077	3.86%	0.062
Paleozoic	457,841	3.40%	30,723	107,870	74,397	3.88%	0.162
Precambrian	2,253,259	16.76%	641,691	1,225,839	872,382	45.51%	0.387
Total, all recharge zones	**13,446,188**	**100.00%**	**1,323,698**	**3,550,173**	**1,917,033**	**100.00%**	**0.143**
Total, sedimentary zones, Paleozoic through Quaternary zones	**11,192,929**	**83.24%**	**682,006**	**2,324,334**	**1,044,651**	**54.49%**	**0.093**
[1] adapted from Hamerlinck and Arneson, 1998							

porosities. This characteristic is illustrated by the rapid seasonal decreases in mountain spring flows. Most groundwater in the Precambrian aquifers discharges to and sustains flows to lakes and mountain streams. As these streams flow basinward, they cross and recharge the younger sedimentary geologic units that crop out along the margins of the structural groundwater basins. The observed high rates of recharge in the Precambrian aquifers are offset by high rates of natural discharge which means that the volume of recharge stored in the Precambrian units is quite low. Groundwater development in the Precambrian aquifer is limited to local springs and low-yield wells.

When all of the Platte River Basin's estimated recharge is considered, it constitutes 7 to 17 percent of total precipitation. If recharge to the Precambrian terrain is discounted, because much of the recharge to these aquifers is discharged to surface waters, total recharge ranges from approximately 4 to 11 percent (**Table 8-2b**) of total precipitation. These estimates encompass the "rule-of-thumb" frequently cited by water resource professionals that 10 percent of precipitation eventually becomes recharge. Finally, the volumes of recharge that enter groundwater storage are further reduced in areas where recharge is "rejected" or discharged as spring flow. Once rejected, it may be evaporated, beneficially used or discharged as streamflow.

6.3 Summary

- Recharge ultimately controls the availability and sustainability of regional groundwater resources, and recharge is controlled directly and indirectly by precipitation. Total average annual precipitation in the Platte River Basin for the 1981-2010 period of record has been estimated as 19,677,577 acre-feet (**Table 8-2a**).
- Recharge controlled by precipitation and soil/vegetation combinations in the Platte River Basin ranges from 0 to 28 inches (Hamerlinck and Arneson, 1998), with the lowest values occurring in the interior basins and the highest in the surrounding mountain ranges.
- Recharge efficiency (recharge as a percentage of precipitation, or R/P) varies based on the factors used the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) to estimate recharge throughout Wyoming.
- Other factors also control recharge and may dominate locally (e.g., solution enhanced fractures); however, the consideration of these factors should confirm the overall pattern of recharge and recharge efficiency from Hamerlinck and Arneson (1998).

Recharge from precipitation to the flat-lying Tertiary, and Mesozoic aquifers in the interior basin areas is generally less efficient than to the upturned Paleozoic and fractured Precambrian aquifers in the uplifted and mountainous areas and the typically alluvial Quaternary aquifers. Recharge is more efficient in some areas of the High Plains Upper Tertiary aquifer. Recharge in the Platte River Basin is most efficient in the higher mountain Precambrian terrains; however, most of the groundwater in this shallow fracture-control aquifer is rejected and discharged to surface waters.

- Because recharge from the Precambrian aquifer is mostly rejected, the best estimate for overall recharge in the Platte River Basin discounts Precambrian recharge volumes and considers only the younger sedimentary aquifers.
- Estimates of average annual recharge in the Platte River Basin is presented as a high/low range consistent with the range of recharge rates mapped over the aquifer outcrop areas and as a "best total" based on the cell-by-cell product of area and rate of recharge.
- Future analyses of recharge may incorporate some of the significant additional factors discussed in **Sections 5.1.3.1 and 5.4** such as the distribution and character of fractures, recharge from surface water bodies and improved quantification of ET rates. Current computational technology and data may allow these analyses on small geospatial areas but cannot yet extend studies of this detail over the entirety of the Platte River Basin.

Chapter 7

Physical and chemical characteristics of hydrogeologic units in the Platte River Basin

Timothy T. Bartos, Laura L. Hallberg, and Melanie L. Clark

The physical and chemical characteristics of hydrogeologic units in the Platte River Basin (PtRB) are described in this chapter of the report. Some descriptions of physical characteristics were modified from Bartos et al. (2006, 2012) and Bartos and Hallberg (2010).

7.1 Platte River Basin

For descriptive and summary purposes, wells from which physical and chemical characteristics were obtained were grouped and summarized using seven broad "geologic/geographic regions" shown in **Figure 7-1**. The seven geographic regions were based primarily on the areal extent of structural and geographic features listed below. The areal extent of these structural and geographic features generally follows the approximate areal extents shown in the statewide Phanerozoic stratigraphic nomenclature chart of Love et al. (1993, Figure 1); however, the areal extent of the central Wyoming basins (north and south) regions also was refined using drainage areas (using 8-digit hydrologic unit codes). The seven regions generally include the following geologic structures and associated geographic areas (these structures and areas are described in **Chapter 2**):

Sweetwater Arch:

- Green River Basin
- Wind River Mountains
- Granite Mountains
- Rattlesnake Hills
- Alcova
- Ferris Mountains
- Freezeout Mountains
- Seminoe Mountains
- Shirley Mountains
- Rawlins Uplift

Central Wyoming basins (south):

- Carbon Basin and adjacent surrounding areas
- Hanna Basin and adjacent surrounding areas
- Great Divide and Green River Basins south of the Granite and Wind River Mountains
- Saratoga Valley
- Laramie Basin

Sierra Madre:

- Sierra Madre

Medicine Bow Mountains:

- Medicine Bow Mountains

Laramie Mountains:

- Laramie Mountains

Central Wyoming basins (north):

- Casper Arch and adjacent areas
- Shirley Basin and adjacent surrounding areas
- Southeastern corner of Wind River Basin

Great Plains:

- Southern Powder River Basin
- Hartville Uplift
- Great Plains/High Plains
- Denver-Julesburg Basin

Lithostratigraphic and corresponding hydrostratigraphic (hydrogeologic) units in the PtRB are shown on **Plates J, K, M, S, T,** and **U**. Lithostratigraphic units for specific structural areas identified on these plates were taken directly from the statewide Phanerozoic stratigraphic nomenclature chart of Love et al. (1993).

For this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are summarized in tabular format (**Plate 3**). The original sources of the data used to construct the summary are listed (see **Sources of Data** at the bottom of the plate). Physical characteristics are summarized to provide a broad summary of hydrogeologic unit characteristics and include spring discharge, well yield, specific capacity, transmissivity, porosity, hydraulic conductivity, and storage (storativity/storage coefficient). Individual data values and corresponding interpretation were utilized and summarized as presented in the

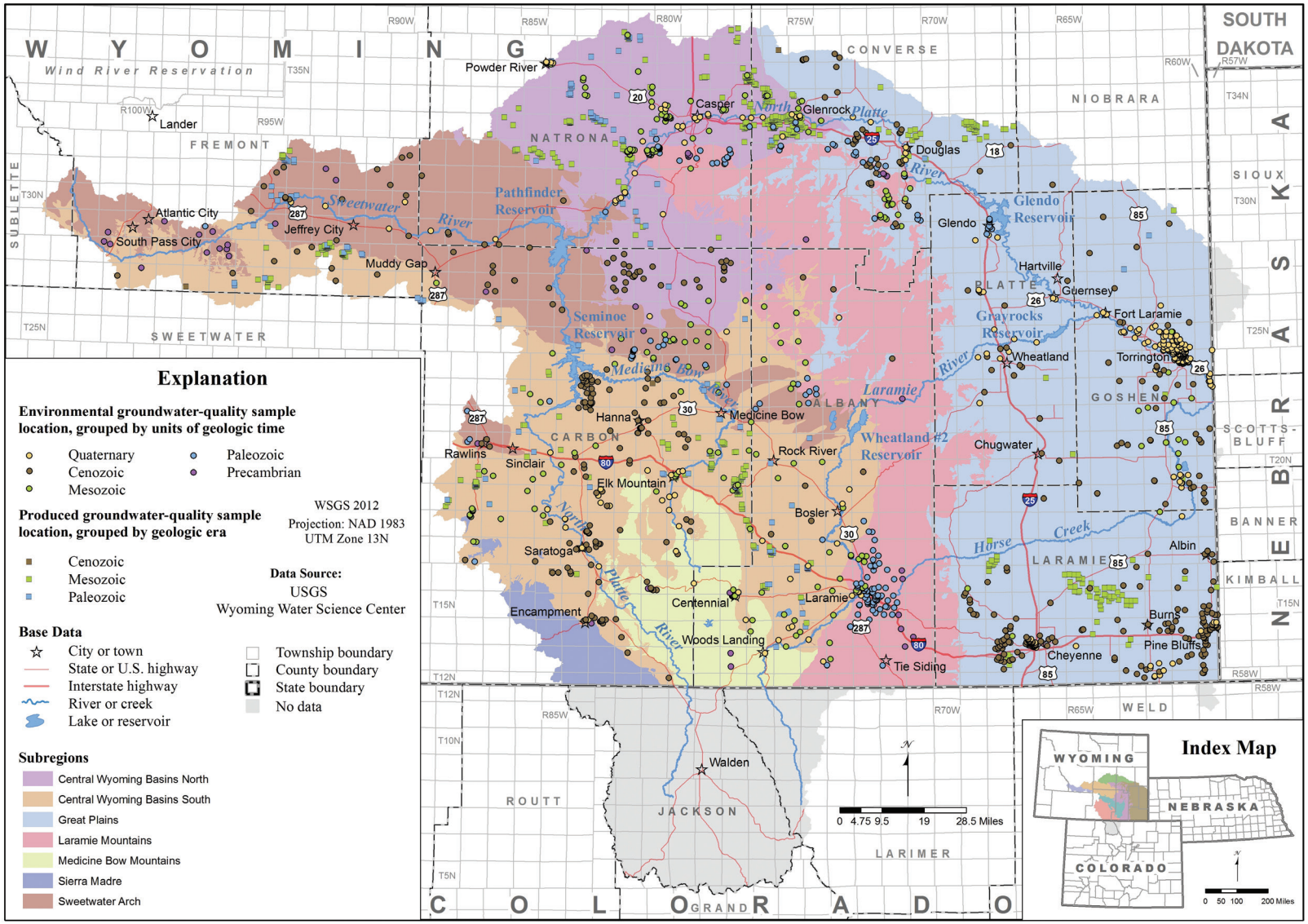


Figure 7-1. Environmental and produced groundwater quality sample locations, grouped by sub-regions, Platte River Basin, Wyoming.

original reports—no reinterpretation of existing hydraulic data (from 1907–2008) was conducted for this study. For example, values of transmissivity derived from aquifer tests were used as published in the original reports, and no reanalysis of previously published aquifer tests was conducted.

7.2 Cenozoic hydrogeologic units

Cenozoic hydrogeologic units are described in this section of the report. Cenozoic hydrogeologic units have been divided into two groups (Quaternary unconsolidated-deposit aquifers and Tertiary hydrogeologic units) for descriptive purposes.

7.2.1 Quaternary unconsolidated-deposit aquifers

The physical and chemical characteristics of Quaternary unconsolidated-deposit aquifers in the PtRB are described in this section of the report. Unconsolidated-deposit aquifers in saturated sediments of Quaternary age (referred to herein as "Quaternary unconsolidated-deposit aquifers") can be highly productive locally and are the source of water for many shallow wells in the PtRB. In the PtRB, saturated Quaternary unconsolidated deposits that contain aquifers include alluvium and colluvium (identified herein as "Quaternary alluvial aquifers"), terrace deposits (identified herein as "Quaternary terrace-deposit aquifers"), dune sand (eolian), and glacial deposits (Rapp et al., 1953, 1957; Morris and Babcock, 1960; Weeks, 1964; Welder and Weeks, 1965; Welder and McGreevy, 1966, Sheet 3; Lowry and Crist, 1967; Herrmann, 1972, 1976; Lowry et al., 1973, Sheet 3; Crist, 1975). The physical and chemical characteristics for each of these four types of Quaternary unconsolidated-deposit aquifers are described together for convenience. Finally, previously constructed groundwater-flow models of Quaternary unconsolidated-deposit aquifers in the PtRB are identified and briefly described.

7.2.1.1 Quaternary alluvial aquifers

The physical and chemical characteristics of Quaternary alluvial aquifers, composed primarily of alluvium in the PtRB, are described in this section of the report. Colluvium, composed of poorly sorted debris at the base of steep slopes or slope wash, is included with alluvium in this report for summary purposes.

Physical characteristics

Alluvium, defined as flood-plain deposits in many reports, is composed primarily of sand and gravel interbedded with finer-grained sediments such as silt and clay, although coarser deposits such as cobbles and boulders occur locally (Rapp et al., 1953, 1957; Morris and Babcock, 1960; Berry, 1960; Weeks, 1964; Welder and Weeks, 1965; Herrmann, 1972, 1976; Lowry et al., 1973; Lowry and Crist, 1967; Crist, 1975). The size of sediments composing the deposits is related primarily to the source of the eroded and transported parent material and the distance the sediments have been transported. Crist and Lowry (1972) noted that alluvium in Natrona County derived from parent material eroded from resistant Precambrian and Paleozoic rocks and Tertiary conglomerate such as along Bates Creek and Wolf Creek has a large percentage of coarse-grained sediments. Conversely, the investigators noted that alluvium from parent material eroded from fine-grained rocks such as clay, shale, and fine sand, such as along Bear Creek, the lower reaches of Stinking Creek, Powder River, and along the central reach of the Middle Fork of Casper Creek, consists of fine-grained sediments. These observations are applicable to all alluvium in the PtRB. Alluvium is found along most major and minor drainages of the PtRB (Love and Christiansen, 1985) (Plate **1**). Because it is primarily associated with stream valleys, the areal extent of alluvium is small in comparison with the full extent of the PtRB (Plate **1**).

The thickness of alluvium in the PtRB varies by stream or river valley and location. Along the Laramie River and Sybille and Chugwater Creeks in the Wheatland Flats area, thickness of alluvium (identified as flood-plain deposits) ranges from 0 to 30 feet (ft) (Weeks, 1964). Rapp et al. (1957) reported alluvium (identified as flood-plain deposits) thickness of 0 to 200 ft or more in Goshen County. Morris and Babcock (1960) reported alluvium thicknesses of 0 to 90 ft in Platte County, with the thickest deposits in the North

Platte River valley near Guernsey; the investigators noted that alluvial deposits underlying the valleys of Elkhorn, Horseshoe, Bear, and Cottonwood Creek ranged from less than 15 ft in the upper reaches to as much as 50 ft in the lower reaches. Burritt (1962, p. 73) reported a maximum alluvium thickness of 30 ft along "minor streams" and the Laramie River south of the city of Laramie in the southern Laramie Basin. Welder and Weeks (1965) reported maximum thicknesses of 37 and 65 ft, respectively, for Bear Creek and North Platte River alluvium in the vicinity of Glendo. Thickness of the alluvium along the Laramie River and its tributaries is likely less than 25 ft (Lowry and Crist, 1967). Lowry and Crist (1967) reported thicknesses of alluvium (identified as flood-plain deposits) as much as 85 ft in Laramie County. Crist and Borchert (1972) reported that alluvium in Lodgepole Creek Valley near Pine Bluffs was as much as 85-ft thick. Lowry et al. (1973, Sheet 3) indicated that alluvium and colluvium generally are 10- to 20- ft thick in the Hanna and Shirley Basins (Plates 1, 2) and surrounding areas, with a maximum reported thickness of 100 ft along Rock Creek. Welder and McGreevy (1966, Sheet 3) indicated that alluvium and colluvium range in thickness from 0 to 50 ft in the Great Divide Basin. The highly permeable North Platte River alluvium, which is used as a source of water for the city of Casper and adjacent areas, is as much as 40 ft in thickness (Gollnitz and Clancy, 2002, and references therein). Much larger thicknesses of North Platte River alluvium are found in some parts of the in the PtRB. For example, Weston Engineering, Inc. (1998b, p. 1-3) reported a maximum thickness of 170 ft for North Platte River alluvium in the city of Guernsey.

Quaternary alluvial aquifers are composed primarily of saturated and permeable alluvium. In the PtRB, alluvial aquifers provide water to many stock, domestic, irrigation, and public-supply wells (Banner Associates, Inc., and TriHydro Corporation, 1995, and references therein; Lidstone and Associates, Inc., 2004, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein). Alluvial aquifers generally are local with small areal extent along streams, and groundwater in the aquifers typically is unconfined (water-table conditions predominate) (Littleton, 1950a, b; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Welder and Weeks, 1965; Welder and McGreevy, 1966; Lowry and Crist, 1967; Herrmann, 1972, 1976; Lowry et al., 1973; Crist, 1975). Alluvial aquifers in the PtRB commonly are in hydraulic connection with adjacent streams and rivers (for example, Babcock and Rapp, 1952; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Welder and Weeks, 1965; Lowry and Crist, 1967; Meyers and Cushman, 1971; Herrmann, 1972, 1976; Crist, 1975; Borchert, 1976, 1985; Glover, 1983; Crist, 1990; Lidstone and Associates, Inc., 2009; Hinckley Consulting and AMEC Earth and Environmental, 2011). Despite small areal extent, alluvial aquifers provide large volumes of water to irrigation and public-supply wells in parts of the PtRB due to large saturated thickness and coarse grain size (Morris and Babcock, 1960; Herrmann, 1972, 1976; Crist, 1975; James M. Montgomery Consulting Engineers, Inc., 1990a; Weston Engineering, 1998b; Gollnitz and Clancy, 2002, and references therein; Lidstone and Associates, Inc., 2004, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein).

Well yields and aquifer physical properties vary substantially (**Plate 3**) in relation to sediment size and sorting, as well as variable saturated thickness that changes in response to aquifer recharge and water withdrawal. Hydrogeologic data describing the Quaternary alluvial aquifers in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Due to areal extent, location, large saturated thickness, and (or) coarse sediment size, the largest well yields obtained from Quaternary alluvial aquifers in the PtRB are associated with the North Platte River and lower reaches of its major tributaries (Rapp et al., 1957; Morris and Babcock, 1960; Herrmann, 1972, 1976; Crist, 1975; Weston Engineering, 1998b; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein). Aquifers in North Platte River alluvium and immediately adjacent upland terrace deposits [defined as the first, second, and third terraces by Rapp et al. (1957)] are in hydraulic connection throughout

much of the North Platte River valley in the vicinity of Torrington. Consequently, the deposits comprise a hydraulically connected groundwater system in the area (Herrmann, 1972, 1976; Crist, 1975; Parks, 1991); Crist (1975) defined this groundwater system as the "valley-fill aquifer." Water obtained from the productive North Platte River alluvial aquifer is used extensively for stock, domestic, and irrigation purposes (for example, Morris and Babcock, 1960; Herrmann, 1972, 1976; Crist, 1975; Parks, 1991; James M. Montgomery Consulting Engineers, Inc., 1990a; Baker and Associates, 1994; Banner Associates, Inc., and TriHydro Corporation, 1995, and references therein; Weston Engineering, 1998b, and references therein; Gollnitz and Clancy, 2002, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein). In addition, the productive North Platte River alluvial aquifer is used to provide water to numerous public water supply systems, including the cities and adjacent areas of Casper, Guernsey, Hartville, Fort Laramie, Lingle, and Torrington (James M. Montgomery Consulting Engineers, Inc., 1990a; Parks, 1991; Baker and Associates, 1994; Banner Associates, Inc., and TriHydro Corporation, 1995, and references therein; TST Inc. et al., 1995a, b; Weston Engineering, 1998b; Gollnitz and Clancy, 2002, and references therein; Lidstone and Associates, 2004).

Two studies indicated that the North Platte River alluvial aquifer in Goshen County is in minimal hydraulic connection with underlying bedrock hydrogeologic units. Along the North Platte River valley in the vicinity of Torrington, Herrmann (1972) concluded that alluvial and terrace-deposit aquifers were minimally hydraulically connected to adjacent or underlying bedrock hydrogeologic units. Weston Engineering (1998b, p. 4-10) indicated that "drilling observations and pump test data" for production wells completed in the North Platte River alluvial aquifer in the vicinity of Guernsey indicated minimal hydraulic connection between the aquifer and underlying Tertiary and Paleozoic bedrock hydrogeologic units.

Recharge to Quaternary alluvial aquifers is from direct precipitation on the deposits, irrigation water, canal and ditch seepage, losing streams/streamflow, and groundwater seepage from underlying hydrogeologic units (Rapp et al., 1953, 1957; Babcock and Bjorklund, 1956; Robinson, 1956; Bjorklund, 1959; Morris and Babcock, 1960; Welder and Weeks, 1965; Libra et al., 1981; Herrmann, 1972, 1976; Lowry and Crist, 1967; Crist, 1975). Recharge to many Quaternary alluvial aquifers is not only from direct infiltration of precipitation and ephemeral and perennial streamflow losses, but also from infiltration of diverted surface water from unlined irrigation canals and ditches as well as from water applied to fields and discharge from underlying aquifers (Littleton, 1950a, b; Robinson, 1956; Rapp et al., 1957; Morris and Babcock, 1960; Burritt, 1962; Welder and Weeks, 1965; Herrmann, 1972, 1976; Crist, 1975; Borchert, 1976, 1985; Libra et al., 1981; Glover, 1983; Hinckley Consulting and AMEC Earth and Environmental, 2011). Welder and Weeks (1965) also noted that releases of large volumes of water from the Glendo Reservoir provided additional recharge to the North Platte River alluvial aquifer in the vicinity of Glendo. Evapotranspiration from Quaternary alluvial aquifers is likely to be highest in areas where crops are grown.

Numerous lakes and ponds present in the southern Laramie Basin in central Albany County, commonly in depressions where the water table intersects the land surface, are fed in part or completely by groundwater from alluvium (Littleton, 1950b; Burritt, 1962). Burritt (1962) noted that many of these "water-table lakes" and ponds form during periods of high runoff in the spring and summer, and that many of them go dry as the summer progresses and runoff and presumably groundwater contribution decrease. The investigator (Burritt, 1962) noted that Mortenson, Meeboer, Soda, and Sevenmile Lakes are permanent water-table lakes. Littleton (1950b) noted that Long Lake and Lake Ione were fed partly by groundwater from alluvium in an abandoned Laramie River stream channel. The investigator (Littleton, 1950b, p. 18) also noted that groundwater in the alluvium of the Laramie River moves into Alkali Basin "where it ultimately is lost through evaporation from the surface of Bamforth Lake." Water levels in some lakes in the southern Laramie Basin are maintained partly or completely by seepage from irrigation or irrigation ditches (for example, Geraud and Keinath, 2004, and references therein).

Discharge from Quaternary alluvial aquifers occurs by evapotranspiration, gaining streams,

seeps, and spring flows, withdrawals from wells, and underflow (Morgan, 1947; Littleton, 1950a, b; Rapp et al., 1953, 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Lowry et al., 1973, Sheet 3; Crist, 1975, 1980, 1990; Parks, 1991). Evapotranspiration from Quaternary alluvial aquifers is likely to be highest in areas where crops are grown. The direction of groundwater flow in most Quaternary alluvial aquifers generally is toward streams or in the direction of streamflow, including as underflow parallel to streamflow (Rapp et al., 1953, 1957; Morris and Babcock, 1960; Weeks, 1964; Welder and Weeks, 1965; Welder and McGreevy, 1966, Sheet 3; Lowry and Crist, 1967; Herrmann, 1972, 1976; Lowry et al., 1973, Sheet 3; Crist, 1975; Glover, 1983; Lidstone and Associates, Inc., 2009).

Underflow from Quaternary alluvial aquifers has been estimated at several locations in the PtRB. Rapp et al. (1957, p. 65) estimated underflow out of the alluvium associated with the North Platte River valley-fill aquifer in Goshen County along the Wyoming-Nebraska state line to range from about 6,500 to 7,000 acre-feet per year. Crist (1975, Table 8) estimated underflow out of the alluvium associated with the North Platte River valley-fill aquifer in Goshen County along the Wyoming-Nebraska state line to be about 570 acre-feet per month (6,800 acre-feet per year).

Chemical characteristics

The chemical characteristics of groundwater from Quaternary alluvial aquifers in the PtRB are evaluated in this section of the report. Locations of groundwater-quality samples collected from Quaternary alluvial aquifers in the PtRB are shown on **Figure 7-1**. Groundwater quality of Quaternary alluvial aquifers is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of Quaternary alluvial aquifers in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that all waters were fresh (concentrations less than or equal to 999 mg/L) (**Appendix E1**, supplementary data tables). TDS concentrations ranged from 252 to 391 milligrams per liter (mg/L), with a median of 269 mg/L.

One characteristic in groundwater from Quaternary alluvial aquifers in the SA exceeded a State of Wyoming water-quality standard and could limit suitability for some uses. On the basis of comparison of concentrations with health-based and aesthetic standards, all water was suitable for domestic use. For agricultural use, one characteristic—SAR in 14 percent of environmental water samples—was measured at a concentration greater than its State of Wyoming agricultural-use (WDEQ Class II) standard of 8. No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in Quaternary alluvial aquifers in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 35 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS concentration is shown on a trilinear diagram (**Appendix G2, diagram A**). TDS concentrations were variable and indicated that most waters were fresh (88 percent of samples), and remaining waters ranged from slightly saline (1,000 to 2,999 mg/L) to moderately saline (3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram A**; supplementary data tables). TDS concentrations ranged from 28 to 5,840 mg/L, with a median of 394 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary alluvial aquifers in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were

suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (100 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), nitrate (11 percent; USEPA MCL of 10 mg/L), and nitrate plus nitrite (9 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (36 percent; USEPA SMCL of 500 mg/L), sulfate (20 percent; SMCL of 250 mg/L), pH (4 percent above upper SMCL limit of 8.5), fluoride (4 percent; SMCL of 2 mg/L), and chloride (4 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (28 percent; WDEQ Class II standard of 200 mg/L), TDS (4 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (4 percent; WDEQ Class II standard of 100 mg/L). Characteristics measured at concentrations greater than livestock-use standards were pH (4 percent above upper limit of the WDEQ Class III standard of 8.5) and TDS (4 percent; WDEQ Class III standard of 5,000 mg/L).

Medicine Bow Mountains

The chemical composition of groundwater in Quaternary alluvial aquifers in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water sample from a well. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (161 mg/L) indicates that the water was fresh. On the basis of the characteristics and constituents analyzed, the quality of water from Quaternary alluvial aquifers in the MBM was suitable for most uses. No characteristics or constituents in the Quaternary alluvial aquifers approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in Quaternary alluvial aquifers in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as nine wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E5**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E5**, supplementary data tables). TDS concentrations ranged from 578 to 928 mg/L, with a median of 664 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary alluvial aquifers in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of ammonia exceeded health-based standards (25 percent; WDEQ Class I standard of 0.5 mg/L). Ammonia is not included in **Appendix E5** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of one characteristic and one constituent exceeded aesthetic standards (SMCLs) for domestic use: TDS (100 percent) and sulfate (50 percent).

For agricultural use, concentrations of one constituent in environmental water samples was measured at greater than State of Wyoming agricultural-use standards: sulfate (50 percent). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in Quaternary alluvial aquifers in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 30 wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram A**). TDS concentrations were variable and indicated that most waters were fresh (47 percent of samples), and

remaining waters ranged from slightly to moderately saline (**Appendix E6**; **Appendix G4**, **diagram A**; supplementary data tables). TDS concentrations ranged from 165 to 8,950 mg/L, with a median of 1,110 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary alluvial aquifers in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (exceeded the proposed MCL, but did not exceed the alternative MCL), uranium (75 percent; MCL of 30 µg/L), selenium (33 percent; MCL of 50 µg/L), nitrate plus nitrite (11 percent), and fluoride (8 percent; MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (71 percent), sulfate (65 percent), and fluoride (17 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (65 percent), selenium (50 percent; WDEQ Class II standard of 20 µg/L), boron (27 percent; WDEQ Class II standard of 750 µg/L), TDS (24 percent), chloride (12 percent), and SAR (6 percent). Characteristics and constituents measured at concentrations greater than livestock-use standards were mercury (100 percent; WDEQ Class III standard of 0.05 µg/L), selenium (33 percent; WDEQ Class III standard of 50 µg/L), TDS (12 percent), sulfate (12 percent; WDEQ Class III standard of 3,000 µg/L), and nitrate plus nitrite (4 percent; WDEQ Class III standard of 100 mg/L).

Great Plains

The chemical composition of groundwater in Quaternary alluvial aquifers in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 129 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, diagram A). TDS concentrations were variable and indicated that most waters were fresh (95 percent of samples), and remaining waters were slightly saline (**Appendix E7**; **Appendix G5**, **diagram A**; supplementary data tables). TDS concentrations ranged from 207 to 1,530 mg/L, with a median of 528 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary alluvial aquifers in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (100 percent of samples analyzed for the constituent exceeded proposed MCL, whereas no samples exceeded the alternative MCL), ammonia (5 percent; WDEQ Class I standard of 0.5 mg/L), nitrate plus nitrite (21 percent), and nitrate (4 percent). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (55 percent), sulfate (9 percent), and pH (1 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (26 percent), SAR (4 percent), and boron (2 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (1 percent above upper limit).

The areal extent of Quaternary alluvial aquifers coincides with much of the rural population and irrigated cropland in the PtRB, making these aquifers particularly susceptible to contamination from human activities. Evidence of groundwater contamination of Quaternary alluvial and terrace-deposit aquifers by human activities in the GP area of the PtRB has been indicated by detection of elevated nitrate concentrations, most notably in the Torrington area (Parks, 1991; Hasfurther et al., 1993; Baker and Associates, 1994; Eddy-Miller and

Gerhard, 1999), as well as by detection of organic compounds such as pesticides (Bartos et al., 2009, and references therein; Eddy-Miller et al., 2013).

Eddy-Miller and Gerhard (1999) used nitrogen isotope data to help determine the source of the nitrate in the groundwater near Torrington. The investigators concluded that the source of most of the nitrate in the groundwater was probably not from human or animal waste, but rather organic soil nitrogen or ammonium, or nitrate fertilizer applied to crops.

7.2.1.2 Quaternary terrace-deposit aquifers

The physical and chemical characteristics of Quaternary terrace-deposit aquifers in the PtRB are described in this section of the report.

Physical characteristics

Like alluvium, terrace deposits are composed of lenticular beds of unconsolidated sand and gravel, and less commonly of cobbles and boulders derived from older sedimentary and crystalline rocks; sorting varies and coarser sediments commonly are interbedded with lenses of finer-grained sediments such as clay and silt (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Welder and McGreevy, 1966, Sheet 3; Lowry and Crist, 1967; Herrmann, 1972, 1976; Crist and Lowry, 1972; Lowry et al., 1973; Crist, 1975). The size of sediments comprising the deposits is related primarily to the source of the eroded parent material and distance transported. Terrace deposit areal extent generally is small, and the deposits typically are found along uplands bordering principal streams of the PtRB (Love and Christiansen, 1985) (Plate **1**); however, areally extensive deposits are found in some areas, most notably in the Pine Bluffs Lowland of southeastern Laramie County, the Wheatland and Muleshoe Flats areas near Wheatland, and the Laramie Basin (Plates 1, 2). Terrace deposits may be present in many different terrace levels alongside streams draining the basin and in adjacent upland areas (for example, Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Crist, 1975).

Terrace-deposit thickness varies substantially in the PtRB and depends on stream or river valley association and location. Along the North Platte River and associated tributaries in the North Platte River valley, deposits can be as much as 210-ft thick (Rapp et al., 1957). In the Wheatland Flats area, thickness ranges from 0 to 85 ft (Morris and Babcock, 1960; Weeks, 1964, table 2). Lowry and Crist (1967, table 1) reported that terrace deposits in Laramie County could be as much as 200-ft thick. Crist and Borchert (1972) reported that terrace deposits in the Pine Bluffs Lowland could be as much as 150-ft thick. In the Hanna and Shirley Basins and surrounding areas, Lowry et al. (1973, Sheet 3) indicated that terrace deposits generally are less than 20-ft thick, but that thicknesses greater than 100 ft are known. Although areally extensive, terrace deposits in the Laramie Basin generally are less than 10 ft in thickness (Morgan, 1947; Robinson, 1956).

Quaternary terrace deposits commonly are topographically high and unsaturated (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Lowry et al., 1973, Sheet 3). In many locations in the PtRB, Quaternary terrace deposits were not saturated prior to irrigation, indicating that recharge of diverted surface water through unlined irrigation canals and ditches and water applied to fields likely is the dominant source of recharge to these terrace-deposit aquifers (Morgan, 1947; Littleton, 1950a; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Lowry et al., 1973, Sheet 3). Topographically high unsaturated terrace deposits that underlie the upland slopes bordering valleys such as those associated with the North Platte River can serve as infiltration areas for recharge of underlying hydrogeologic units (Rapp et al., 1957).

Where saturated and permeable, Quaternary terrace deposits can contain aquifers. Quaternary terrace-deposit aquifers can produce enough water locally for stock or domestic use, and possibly for small to moderate irrigation use, although well yield likely will fluctuate based on the amount of recharge (for example, Morris and Babcock, 1960; Weeks, 1964). Groundwater in terrace-deposit aquifers typically is unconfined (water-table conditions predominate). Quaternary terrace-deposit aquifers in the Wheatland Flats, Pine Bluffs Lowland, and North Platte River valley

areas are important aquifers used to supply water for stock and domestic uses (Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Crist and Borchert, 1972). In parts of these areas, sufficient volumes of water can be obtained from Quaternary terrace-deposit aquifers for public-supply or irrigation use due to large saturated thickness, coarse sediment size, and sufficient recharge (Rapp et al., 1957; Lowry and Crist, 1967; Crist and Borchert, 1972). In parts of the PtRB, Quaternary alluvial aquifers and Quaternary terrace-deposit aquifers can be in direct hydraulic connection with one another and (or) with adjacent or underlying Tertiary bedrock aquifers (Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Crist and Borchert, 1972; Crist, 1975, 1980, 1990; Borchert, 1985).

Well yields and aquifer physical properties of Quaternary terrace-deposit aquifers are highly variable (**Plate 3**), reflecting the variable size and sorting of sediments comprising the deposits, as well as saturated thickness that changes in response to different amounts of aquifer recharge and water withdrawal. Hydrogeologic data describing the Quaternary terrace-deposit aquifers in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3.**

Quaternary terrace-deposit aquifer thickness has been mapped in southeastern Laramie County. Estimates by Lowry and Crist (1967, Figure 12) indicated that saturated thickness in the Pine Bluffs Lowland was 80 ft or more in 1965. Subsequently, Crist and Borchert (1972, Figure 6) estimated saturated thickness for the same general area in 1971, and they reported thicknesses as large as 110 ft.

Although some recharge to Quaternary terrace-deposit aquifers is from direct infiltration of precipitation, most is from infiltration of diverted surface water through unlined irrigation canals and ditches and water applied to fields (Morgan, 1947; Littleton, 1950a; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Lowry et al., 1973, Sheet 3; Crist, 1975; Parks, 1991). Consequently, water levels in terrace-deposit aquifers typically fluctuate in response to seasonal application of water for irrigation purposes (for example, Rapp et al., 1957; Morris and Babcock, 1960; Crist, 1975). In some terrace-deposit aquifers, groundwater moves downward and provides direct recharge to underlying Tertiary bedrock aquifers such as the White River aquifer/confining unit (Crist and Borchert, 1972).

Recharge to Quaternary terrace deposits in the southern Laramie Basin in Albany County is from direct infiltration of precipitation (Littleton, 1950b; Burritt, 1962, p. 71). Wells completed in the terrace deposits in this area generally provide water only temporarily after periods of precipitation and commonly "dry up" shortly thereafter.

Discharge from Quaternary terrace-deposit aquifers occurs by evapotranspiration, gaining streams, seeps, and spring flows, withdrawals from wells, and underflow (Morgan, 1947; Littleton, 1950a, b; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Lowry et al., 1973, Sheet 3; Crist, 1975; Parks, 1991). Evapotranspiration from Quaternary terrace-deposit aquifers is likely to be highest in areas where crops are grown. Underflow out of the terrace deposits associated with the North Platte River valley-fill aquifer in Goshen County along the Wyoming-Nebraska State line was estimated to be about 22,000 acre-feet per year by Rapp et al. (1957, p. 67) and about 860 acre-feet per month (or about 10,000 acre-feet per year) by Crist (1975, Table 8, p. 32).

The direction of groundwater flow in terrace-deposit aquifers generally is toward the principal surface drainage with a slope the same as the slope of the land surface (for example, Littleton, 1950a, b; Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Parks, 1991). Underlying bedrock surface irregularities can locally alter the direction of groundwater flow in Quaternary terrace-deposit aquifers, as observed in the Torrington area (Rapp et al., 1957; Parks, 1991).

Chemical characteristics

The chemical characteristics of groundwater from Quaternary terrace-deposit aquifers in the PtRB are evaluated in this section of the report. Groundwater quality of the Quaternary terrace-deposit aquifers is described in terms of a water's suitability for domestic, irrigation, and livestock

use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Central Wyoming basins (south)

The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the CBS was characterized and the quality evaluated on the basis of environmental water samples from as many as 5 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E2**, supplementary data tables). TDS concentrations ranged from 158 to 512 mg/L, with a median of 368 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary terrace-deposit aquifers in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (20 percent; USEPA SMCL of 500 mg/L) and fluoride (20 percent; SMCL of 2 mg/L).

For agricultural use, concentrations of one constituent in environmental water samples was measured at greater than State of Wyoming agricultural-use standards: sulfate (20 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the CBN was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E6**. The TDS concentration from the spring (2,890 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L).

Concentrations of some characteristics and constituents in water from Quaternary terrace-deposit aquifers in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. All environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (in the one sample analyzed for this constituent), sulfate (in the one sample analyzed for this constituent, the concentration exceeded the SMCL of 250 mg/L), and chloride (in the one sample analyzed for this constituent, the concentration exceeded the SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were TDS (in the one sample analyzed for this characteristic, the concentration exceeded the WDEQ Class II standard of 2,000 mg/L), chloride (in the one sample analyzed for this constituent, the concentration exceeded the WDEQ Class II standard of 100 mg/L), sulfate (in the one sample analyzed for this constituent), and boron (50 percent; WDEQ Class II standard of 750 µg/L). Concentrations of two constituents were measured at greater than State of Wyoming livestock-use standards: mercury (in the one sample analyzed for this constituent; WDEQ Class III standard of 0.05 µg/L) and boron (50 percent; WDEQ Class III standard of 5,000 µg/L).

Great Plains

The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 47 wells. Summary statistics calculated for available

constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram B**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram B**; supplementary data tables). TDS concentrations ranged from 234 to 727 mg/L, with a median of 542 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary terrace-deposit aquifers in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (67 percent of samples analyzed for the constituent exceeded the proposed MCL, whereas no samples exceeded the alternative MCL), nitrate plus nitrite (37 percent; MCL of 10 mg/L), and nitrate (9 percent; MCL of 10 mg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (62 percent) and sulfate (8 percent).

For agricultural and livestock use, concentrations of some constituents exceeded State of Wyoming standards in the GP. One constituent in environmental water samples was measured at concentrations greater than agricultural-use standards: sulfate (8 percent). One constituent exceeded applicable State of Wyoming livestock water-quality standards: mercury (in the one sample analyzed for this constituent).

7.2.1.3 Aquifers in Quaternary dune sand (eolian) deposits

The physical and chemical characteristics of aquifers in Quaternary dune sand (eolian) deposits in the PtRB are described in this section of the report.

Physical characteristics

Eolian sand (windblown) and loess deposits (dune sand) of Quaternary age are found in different parts of the PtRB (Love and Christiansen, 1985) (**Plate 1**). Large areas of dune sand are located in the Ferris and Seminoe dune fields in the northwestern part of Carbon County near Lamont and Ferris (only part of these dune fields are in the PtRB study area); north and west of Torrington in Goshen County; and east of Chugwater in Platte County (**Plate 1**). Composition of dune materials in the Ferris and Seminoe dune fields can range from clay to coarse sand, but is primarily well sorted fine-grained sand in the large dunes (Lowry et al., 1973; Gaylord, 1982, 1989). The primary geologic source for the Ferris and Seminoe dunes is the Eocene-age Battle Spring Formation to the west, with a secondary geologic source being the Killpecker dune field that is west of the Battle Spring Basin in Sweetwater County (Gaylord, 1982, 1989). The Cretaceous and Paleocene rocks exposed along the Lost Soldier Divide also contributed a minor amount of material to the dunes (Gaylord, 1982). The dunes develop in regions characterized by cool annual temperatures, low precipitation, and persistent strong winds (Gaylord, 1989). These deposits range in thickness from 0 to about 140 ft in the Ferris and Seminoe dune fields (Rioux and Staatz, 1974; Gaylord, 1989, p. 270). Eolian deposits east of Chugwater in Platte County are composed of fine-grained sand that is as much as 50-ft thick (Rapp et al., 1957, Table 1, p. 20). Dune sand in Goshen County generally is unsaturated but does provide "an excellent medium for infiltration" of recharge from streams, canals, and precipitation to underlying hydrogeologic units (Rapp et al., 1957, p. 41). Dune sand deposits south of the Ferris Mountains can serve as infiltration areas for recharge to underlying hydrogeologic units (Welder and McGreevy, 1966, Sheet 3). In conclusion, areas of dune sand saturation in the PtRB are limited and thus, aquifers in these deposits are uncommon and are rarely used as a source of water.

Chemical characteristics

The chemical characteristics of groundwater from Quaternary dune sand (eolian) deposits in the PtRB are evaluated in this section of the report. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table**

5-2), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Central Wyoming basins (north)

The chemical composition of groundwater in Quaternary dune sand (eolian) deposits in the CBN was characterized and the quality evaluated on the basis of environmental water samples from as many as 9 wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (67 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E6**, supplementary data tables). TDS concentrations ranged from 466 to 3,260 mg/L, with a median of 1,340 mg/L.

Concentrations of some characteristics and constituents in water from Quaternary dune sand (eolian) deposits in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: nitrate plus nitrite (56 percent; USEPA MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (89 percent; USEPA SMCL of 500 mg/L), sulfate (89 percent; SMCL of 250 mg/L), and pH (11 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (89 percent; WDEQ Class II standard of 200 mg/L), TDS (22 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (44 percent; WDEQ Class II standard of 100 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (11 percent above upper WDEQ Class III limit of 8.5).

Great Plains

The chemical composition of groundwater in Quaternary dune sand (eolian) deposits in the GP was characterized and the quality evaluated on the basis of samples collected from two wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. On the basis of the characteristics and constituents analyzed for, the quality of water from dune sand (eolian) deposits in the GP was suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.1.4 Aquifers in Quaternary glacial deposits

The physical and chemical characteristics of aquifers in Quaternary glacial deposits in the PtRB are discussed in this section of the report.

Physical characteristics

Quaternary glacial deposits can be found in the Sierra Madre and Medicine Bow Mountains (**Plate 1**) (Love and Christiansen, 1985). Lowry et al. (1973, Sheet 3) described these materials as poorly sorted silt, sand, gravel, and boulders. Few wells are completed in these deposits in the PtRB.

Chemical characteristics

The chemical characteristics of groundwater from Quaternary glacial deposits in the PtRB are evaluated in this section of the report. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Central Wyoming basins (south)

The chemical composition of groundwater in the Quaternary glacial deposits in the CBS was

characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration from the well (92 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L).

On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary glacial deposits in the CBS was suitable for all uses. No characteristics or constituents in the glacial deposits approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Quaternary glacial deposits in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration from the well (44 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L).

On the basis of the characteristics and constituents analyzed for, the quality of water from glacial deposits in the MBM was suitable for all uses. No characteristics or constituents in the glacial deposits approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Groundwater-flow models

In this section the report, groundwater-flow models of Quaternary unconsolidated-deposit aquifers in the PtRB are identified and briefly described in order of publication. Modeling results are not described herein but are available in the identified publications.

Herrmann (1972, 1976) constructed a groundwater-flow model of the North Platte River alluvial aquifer, composed of Quaternary unconsolidated deposits (alluvium and terrace deposits) in the lower North Platte River valley in central Goshen County, Wyoming. The model was custom-written by the author and was constructed using "a finite difference, iterative implicit method solving the time-dependent flow equations" (Herrmann, 1976, p. 377). The groundwater-flow model was constructed as part of a larger study attempting to improve understanding of the North Platte River alluvial aquifer in the study area, including interaction with adjacent bedrock aquifers, effects of application of diverted surface waters for irrigation, and leakage from irrigation canals such as the Fort Laramie and Interstate canals. This improved understanding of North Platte River alluvial aquifer hydrology then was used to construct the groundwater-flow model to simulate the effects of current and hypothetical surface-water and groundwater irrigation withdrawals on groundwater levels and streamflow.

Crist (1975) also conducted a study and constructed a groundwater-flow model of the North Platte River alluvial aquifer in the lower North Platte River valley in central Goshen County, Wyoming. This study and associated groundwater-flow model greatly expanded upon the work of Herrmann (1972) by collecting extensive hydrologic data, and constructing a very detailed water budget; this additional information was used to further refine understanding of a 140-mi.^{2} area of the North Platte River alluvial aquifer in the study area, including interaction with adjacent bedrock aquifers, effects of application of diverted surface waters for irrigation, and leakage from irrigation ditches and canals. The investigator noted that the groundwater-flow model constructed previously by Herrmann (1972) "was not suitable for the State Engineer to use as a guide for administration of water rights in the valley" (Crist, 1975, p. 4). The North Platte River alluvial aquifer was modeled using the finite-difference model of Pinder (1970). The groundwater-flow model was calibrated and then used to simulate the effects of two hypothetical conditions: sealing the Interstate Canal channel to prevent seepage from the canal and leaving water in the Interstate Canal during the nonirrigation season to allow seepage from the canal all year. The model simulated these hypothetical conditions for a 2-year period to predict the location(s) of the largest groundwater-level changes and to predict the effect these conditions might have on groundwater contributions to North Platte River streamflow.

Glover (1983) constructed a groundwater-flow model of the Bates Creek alluvial aquifer in a 55-mi.^{2} area in southeastern Natrona County southwest of Casper, Wyoming. In the study, the alluvial aquifer was defined as an unconfined aquifer composed of saturated unconsolidated deposits of Quaternary age along Bates Creek and its tributaries, including saturated eolian deposits. The Bates Creek alluvial aquifer was modeled using the finite-difference model of Trescott et al. (1976) as modified by Hoxie (1977, p. A1–24) to account for the interaction between the aquifer and streams. The groundwater-flow model was constructed to evaluate the relation between Bates Creek and its tributaries with the associated alluvial aquifer. Hydrologic data collected during 1977 and 1978 were used to construct and calibrate the model under steady-state and transient conditions. Study emphasis was placed on understanding the effects of current and predicted irrigation groundwater withdrawals on streamflow. Finally, three different water-management scenarios were simulated: (1) no groundwater pumping; (2) pumping by all existing wells; and (3) pumping by all existing and proposed wells.

Crist (1990) attempted to construct a groundwater-flow model of the groundwater system composed of Quaternary unconsolidated deposits and Tertiary bedrock aquifers on both sides of the North Platte River in south-central Carbon County. The investigator indicated that construction of the groundwater-flow model was unsuccessful because more data were needed, including measurement of inflow and outflow of streams, measurement of the distribution of stream diversions for irrigation, and seepage measurements on streams throughout the irrigation season. In addition, the investigator recommended additional test-hole drilling to provide groundwater levels, estimate saturated alluvium thickness, and estimate aquifer hydraulic conductivity.

Parks (1991) constructed a groundwater-flow model of the groundwater system composed of Quaternary alluvial and terrace-deposit aquifers in a 50-mi.^{2} area near Torrington. The model was constructed using the then-current version of the finite-difference model MODFLOW (McDonald and Harbaugh, 1984), and the investigator used the single-layer groundwater-flow model to improve understanding of nitrate contamination in the groundwater system of the area. Interactions between several surface-water features (North Platte River, Rawhide Creek, Arnold Drain, and Interstate Canal) and the groundwater system were incorporated into the groundwater-flow model. Upon completion of a steady-state simulation, transient simulations were used to evaluate seasonal (summer and fall) changes in groundwater levels and groundwater-flow direction.

Banner Associates, Inc., and TriHydro Corporation (1997) constructed a groundwater-flow model of the groundwater system composed of Quaternary alluvial and terrace-deposit aquifers in the vicinity of the Torrington golf course. Using data collected during August 1996 and February 1997, and from the Torrington wellhead protection program, the investigators used a proprietary model application developed by TriHydro (identified as "TIMES"; no citation for model code provided in report) to evaluate the effects of hypothetical well-field construction in the vicinity of the golf course. Emphasis was placed on evaluation of the effects of different well-field configurations on groundwater quality in the area with known nitrate contamination, and evaluation of the relation between the aquifer system and the North Platte River. The TIMES groundwater-flow model "uses finite element numerical simulations for predicting fluid flow and pollutant transport" and "can be used in a variety of groundwater predictive analysis studies" (Banner Associates, Inc., and TriHydro Corporation, 1997, p. 3-2). The section of the report describing the model does not identify details of model construction and provides limited information describing subsequent simulations.

Weston Engineering (1998b) constructed a groundwater-flow model of the North Platte River alluvial aquifer for the city of Guernsey and adjacent areas. In the study, the alluvial aquifer was defined as an unconfined aquifer composed of saturated Quaternary alluvium. The North Platte River alluvial aquifer was modeled using the finite-difference MODFLOW groundwater-flow model. The groundwater-flow model consisted of two layers—an upper layer composed of the unconsolidated alluvial aquifer and an underlying low-permeability layer composed of two consolidated (bedrock) lithostratigraphic

units (Arikaree and Hartville Formations). The groundwater-flow model was constructed to evaluate alluvial aquifer groundwater-flow directions and interaction with the North Platte River for establishment of wellhead protection areas. After the steady-state model was calibrated, the particle tracking program associated with MODFLOW, MODPATH (Pollock, 1994), was used to delineate wellhead protection areas for individual public-supply wells.

7.2.2 Tertiary hydrogeologic units

Tertiary hydrogeologic units composed of sedimentary rocks contain the most abundant and widely used shallow aquifers in the PtRB. Because the High Plains aquifer or aquifer system is the most widely used aquifer or aquifer system in the PtRB and in Wyoming, Tertiary hydrogeologic units comprising or underlying the High Plains aquifer or aquifer system in the Great Plains area of the PtRB are identified and described first. Subsequently, Tertiary hydrogeologic units in other parts of the PtRB are identified and described. Locations of groundwater-quality samples from Tertiary hydrogeologic units are shown in **Figure 7-1**.

7.2.2.1 High Plains aquifer system

The High Plains aquifer or aquifer system is present in parts of five counties in southeastern Wyoming (**Plate 4**). The High Plains aquifer system overlies an area of 8,190 mi.^{2} in southeastern Wyoming (Gutentag and Weeks, 1980). Eight percent of Wyoming is located within the High Plains aquifer system, and 5 percent of the aquifer system is located within the State (Gutentag and Weeks, 1980). On the basis of withdrawals for irrigation, public-supply, and industrial use, the High Plains aquifer system is the most used source of groundwater in Wyoming (Boughton et al., 2006, Figure 4). Throughout much of southeastern Wyoming, the High Plains aquifer system is the predominant groundwater resource for agricultural (irrigation), municipal, industrial, stock, and domestic uses (TriHydro Corporation, 2006a, b, c). Withdrawal of groundwater for irrigation is the largest use of water from the High Plains aquifer system in southeastern Wyoming (TriHydro Corporation, 2006a, b, c).

The regional High Plains aquifer system in southeastern Wyoming is described in this section of the report. Much of this description was taken from or modified from Bartos et al. (2013). The Tertiary lithostratigraphic units composing or underlying the aquifer system are identified, the hydrostratigraphy is described and defined, and the physical and chemical characteristics of the individual hydrogeologic units composing the aquifer system are described. Finally, groundwater-flow models composed of parts of or the entire High Plains aquifer system are identified and briefly described.

Lithostratigraphic units

In southeastern Wyoming, the High Plains aquifer system can be composed of as many as four saturated Cenozoic lithostratigraphic units, including Quaternary-age unconsolidated deposits, the Miocene-age Ogallala Formation, the Miocene- and Oligocene-age Arikaree Formation, and the late Eocene- and early Oligocene-age White River Group or Formation (last two columns in **Figure 7-2**). The Cenozoic lithostratigraphic units unconformably overlie the Late Cretaceous Lance Formation. The areal extent of the aquifer system and associated lithostratigraphic units in southeastern Wyoming are shown on **Plate 4**.

Alternating episodes of fluvial (stream-laid) and eolian (windborne) deposition and erosion created the Cenozoic (Quaternary and Tertiary) sedimentary rocks composing the High Plains aquifer system in southeastern Wyoming. The Quaternary-age unconsolidated deposits (alluvium and terrace deposits) were deposited by eastward-flowing streams (Lowry and Crist, 1967). Alluvium was deposited from the erosion of the uplift to the west or in situ erosion of Tertiary rocks. Terrace deposits are erosional remnants of alluvium once deposited along former or current stream valleys. Tertiary rocks composing the aquifer system can be divided into two major groups: an older, more homogenous group mostly composed of very fine- to fine-grained volcaniclastic rocks (derived from pyroclastic volcanic material and also described

Erathem	System	Series	Lithostratigraphic unit of Love et al. (1993)		Hydrogeologic role/unit inferred from Lowry and Crist (1967)[3], Crist and Borchert (1972)[3], and numerous earlier studies[4] in southeastern Wyo.	Hydrogeologic unit of Borchert (1976) [Albin and LaGrange areas, Goshen and Laramie Counties, Wyo.]	Hydrogeologic unit of Lines (1976) and Hoxie (1977; 1979a,b; 1983) [Wheatland Flats, Dwyer, and Muleshoe Flat areas, Platte County, Wyo.]	Hydrogeologic unit of Crist (1977) [Lusk area, Niobrara and northern Goshen Counties, Wyo.]	Hydrogeologic unit of Crist (1980) and Cooley and Crist (1981) [Laramie County, Wyo., and adjacent part of Colo.]		Hydrogeologic unit of Gutentag and Weeks (1980), Weeks and Gutentag (1981), Avery and Pettijohn (1984), and Gutentag et al. (1984), [Parts of Colo., Kans., Nebr., N.Mex., Okla., S.Dak., Tex., and Wyo.]	
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvial and terrace deposits		Local aquifers[5]	Not discussed	Not discussed	Alluvium locally in hydraulic connection where adjacent stream is perennial	Local aquifers[5]	Aquifer system[5]	Local aquifers[5]	High Plains aquifer system[5]
	Tertiary	Miocene	Ogallala Formation		Aquifer	Aquifer	Arikaree aquifer/aquifer system	Not present in study area	Aquifer		Aquifer	
			Arikaree Formation		Aquifer	Aquifer		Aquifer	Aquifer		Aquifer	
		Oligocene	White River Group or Formation[1,2]	Brule Formation[2]	Aquifer/ confining unit[6]	Aquifer/ confining unit[6]	Aquifer/ confining unit[6,7]	Not discussed	Aquifer[6]		Aquifer/ confining unit[8]	
		Eocene[1]		Chadron Formation[1,2]	Aquifer/ confining unit[6]	Not discussed	Not discussed				Confining unit with local aquifers[9]	

Dashed line indicates possible hydraulic connection with underlying or overlying hydrogeologic unit.

[1]Historically, the Chadron Formation has been considered Oligocene in age (Love et al., 1993, and references therein). Revision of the Eocene-Oligocene boundary stratotype to about 34 million years before present or mega-annum (34 Ma) (for example, Berggren et al., 1992; Obradovich et al., 1995), and radiometric age-dating of ash beds in the White River Group or Formation in Wyoming suggesting an age older than 34 Ma (Prothero and Swisher, 1992), infers the Chadron Formation is late Eocene in age (Swinehart and Diffendal, 1997).

[2]"White River" not elevated to Group rank (and not divided into Brule and Chadron Formations) and the unit is defined as a formation in parts of southeastern Wyoming including much of Laramie County (Love and Christiansen, 1985; Love et al., 1993; Ver Ploeg et al., 1998, 2000, and references therein).

[3]Hydrogeologic role of lithostratigraphic units defined for Laramie County (Lowry and Crist, 1967) and southeastern Laramie County (Crist and Borchert, 1972).

[4]See Knight and Morgan (1937), Burleigh et al. (1938), Dockery (1940), Foley (1942), Morgan (1946), Babcock and Rapp (1952), Visher and Babcock (1953), Rapp et al. (1953, 1957), Visher et al. (1954), Babcock and Bjorkland (1956), Bjorkland (1959), Morris and Babcock (1960), Weeks (1960, 1964), Welder and Weeks (1965), and Herrmann (1972).

[5]Local aquifers in Quaternary unconsolidated deposits can be hydraulically connected laterally or vertically to underlying Tertiary aquifers of the High Plains aquifer system; where hydraulically connected, they are part of the aquifer system.

[6]Brule and (or) Chadron Formations (all or upper part) may be considered aquifers and in hydraulic connection with overlying Tertiary and Quaternary aquifers where permeable (coarse-grained deposits or zones of secondary permeability). Both formations function as lower confining unit(s) to overlying Tertiary and Quaternary aquifers where impermeable.

[7]Brule Formation of White River Group considered part of Arikaree aquifer/aquifer system in western part of study area where permeable.

Hydrogeologic unit of Libra et al. (1981) [Denver-Julesberg Basin, southeastern Wyo.]		Hydrogeologic unit of Crist (1983) [Wheatland Flats area, Platte County, Wyo.]		Hydrogeologic unit of Borchert (1985) [LaGrange area, Goshen and Laramie Counties, Wyo., and small area in western Nebr.]		Hydrogeologic unit of Wyoming Statewide Framework Plan (WWC Engineering et al., 2007, Figure 4-9) [Statewide]	Hydrogeologic unit used in this report (where White River Group or Formation is undivided) [southeastern Wyo.]		Hydrogeologic unit used in this report (where White River Group is divided into Brule and Chadron Formations) [southeastern Wyo.]	
Quaternary aquifers		Local aquifers[5]	Aquifer[10]	Local aquifers[5]	LaGrange aquifer[11]	Major aquifer-alluvial	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,12]	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,13]
Major aquifer	Tertiary aquifer system	Not present in study area		Not present in study area		Major aquifer-sandstone	Ogallala aquifer		Ogallala aquifer	
		Aquifer		Not present or not part of LaGrange aquifer		Major aquifer-sandstone	Arikaree aquifer		Arikaree aquifer	
Aquitard with discontinuous aquifers[6]		Not discussed		Aquifer		Marginal aquifer	White River aquifer/ confining unit[12]		Brule aquifer/confining unit[8]	
Aquitard with discontinuous aquifers[8]									Confining unit with local aquifers-Chadron aquifer/ confining unit[9,13]	

[8]Brule Formation of White River Group considered an aquifer and part of High Plains aquifer system only where permeable (coarse-grained deposits or zones of secondary permeability) and in hydraulic connection with overlying Arikaree and Ogallala aquifers. Formation functions as lower confining unit to High Plains aquifer system where impermeable.

[9]Regionally, the U.S. Geological Survey does not consider the Chadron Formation to be part of the High Plains aquifer system, and the unit is classified as a confining unit or confining unit with local aquifers underlying the High Plains aquifer system; however, regional U.S. Geological Survey potentiometric-surface maps of the aquifer system include the formation where exposed at land surface in the Goshen Hole area in southeastern Wyoming (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984).

[10]Aquifer divided into an "upper aquifer" composed of "saturated terrace deposits and the upper part of the Arikaree where the Arikaree is exposed in Wheatland Flats" and "alluvium along Rock Creek-Wheatland Creek, Sybille Creek, Laramie River, and Chugwater Creek," and a "lower aquifer composed of the saturated Arikaree Formation below a depth of 100 feet and all wells deeper than 100 feet" (Crist, 1983, p. 2). The division of the Arikaree Formation into two "zones or units" or aquifers reflects earlier work by Morris and Babcock (1960) and Weeks (1964).

[11]LaGrange aquifer composed of saturated alluvium and both the Brule and Chadron Formations of the White River Group. Ogallala Formation not present in study area. Arikaree Formation, where present in study area, is not part of LaGrange aquifer.

[12]Undivided White River Group or Formation and Brule and Chadron Formations of the White River Group considered aquifers and part of the High Plains aquifer system only where permeable (coarse-grained deposits or zones of secondary permeability). Units function as lower confining unit to High Plains aquifer system where impermeable.

[13]Chadron Formation (or parts of Chadron Formation) considered to be in hydraulic connection with and part of High Plains aquifer system in some areas in southeastern Wyoming by some investigators, most commonly where formation is exposed at land surface and located laterally or vertically adjacent to other Tertiary lithostratigraphic units (Ogallala, Arikaree, and Brule Formations) (for example, Rapp et al., 1957; Borchert, 1985).

Figure 7-2. Relation of Cenozoic lithostratigraphic units to hydrogeologic units, High Plains aquifer system, southeastern Wyoming. Modified from Bartos et al. (2013).

as and considered equivalent to "tuffaceous" or "vitric" in many publications) primarily of eolian origin, and secondarily of fluvial origin, represented by the late Eocene- to early Oligocene-age White River Group or Formation and the Arikaree Formation; and a younger, coarser grained and more heterogeneous group of rocks composed mostly of epiclastic (derived from weathering or erosion) rocks primarily of fluvial/alluvial origin, represented by the Ogallala Formation (Stanley, 1976, and references therein; Swinehart et al., 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). Paleosols (fossil soils) occur in all three Tertiary lithostratigraphic units (Retallack, 1983; Swinehart et al., 1985, and references therein; Swinehart and Diffendal, 1997, and references therein; LaGarry, 1998; Terry, 1998).

The Ogallala Formation is a complex sequence of cuts and fills composed mostly of fluvial sediments with minor amounts of volcanic ash. This complex alluvial sequence of cuts and fills is composed of a heterogeneous mixture of unconsolidated and (or) weakly to firmly cemented gravel, sand, silt, and clay (when consolidated/cemented, these lithologies are equivalent to conglomerate, sandstone, siltstone, and mudstone, respectively) with minor amounts of volcanic ash (Foley, 1942; Morgan, 1946; Minick, 1951; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Stanley, 1971, 1976; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Diffendal, 1984; Swinehart et al., 1985; Swinehart and Diffendal, 1997, and references therein). Thin lenses of well-cemented gravel, sand, and silt cemented primarily with calcium carbonate (caliche or calcrete) and less commonly with silica (silcrete) occur locally, and these lenses or beds are referred to as "mortar beds" in many publications; these cemented lenses or beds are resistant to erosion and often form ledges or caprocks. Lowry and Crist (1967, Table 1) reported a maximum thickness of about 330 ft for the Ogallala Formation in Laramie County.

In contrast to the Ogallala Formation, the White River Group or Formation and Arikaree Formation are composed mostly of valley fills of eolian volcaniclastic material transported into Wyoming from explosive volcanism in areas located to the west (Sato and Denson, 1967; Stanley, 1976, and references therein; Singler and Picard, 1979a, b; Swinehart et al., 1985, and references therein; Swinehart and Diffendal, 1997, and references therein; Larson and Evanoff, 1998). Some stream-laid sediment also is present in the units, most commonly at the bases of the geologic units. Some of the eolian volcaniclastic material has been reworked and re-transported as fluvial deposits.

The Arikaree Formation is composed of friable volcaniclastic, calcareous, very fine- to fine-grained sandstone interbedded with lenses of siltstones, and volcanic ash (Minick, 1951; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Sato and Denson, 1967; Stanley, 1976; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Swinehart et al., 1985). Reported thickness of the Arikaree Formation varies substantially in southeastern Wyoming: 0 to about 450 ft in Laramie County (Lowry and Crist, 1967, Table 1); 0 to 1,000 ft or more in Goshen County (Rapp et al., 1957, p. 21); 0 to about 1,200 ft in Platte County (Morris and Babcock, 1960, Table 1); and 0 to 600 ft or more in Niobrara County (Whitcomb, 1965, Table 3).

The White River Group or Formation is characterized by massive, argillaceous (clayey), calcareous mudstones (commonly siltstone), interbedded with minor amounts of locally occurring sandstone, conglomerate, and volcanic ash beds (Foley, 1942; Morgan, 1946; Gray, 1947; Brady, 1949; Minick, 1951; Rapp et al., 1953; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Sato and Denson, 1967; Denson and Chisholm, 1971; Crist and Borchert, 1972; Stanley, 1976; Singler and Picard, 1979a, b; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Swinehart et al., 1985; Swinehart and Diffendal, 1997; Bartos et al., 2013). In many locations, the "White River" is divided into an upper part (Brule Formation) and a lower part (Chadron Formation), and consequently, elevated to group rank. Reported thickness estimates of the White River Group or Formation vary substantially in southeastern Wyoming: 0 to about 500 ft for the White River Group or Formation (undivided) in Laramie County (Lowry and Crist, 1967, Table

1); 0 to about 450 ft for the Brule Formation, and 0 to 245 ft or more for the Chadron Formation in Goshen County (Rapp et al., 1957, p. 21); 0 to about 420 ft for the Brule Formation, and 0 to about 700 ft for the Chadron Formation in Platte County (Morris and Babcock, 1960, Table 1); and 0 to 500 ft or more for the White River Group or Formation (undivided) in Niobrara County (Whitcomb, 1965, Table 3). All three (or four if "White River" divided) Tertiary lithostratigraphic units unconformably overlie the predominantly fluvial Late Cretaceous Lance Formation (**Plate M**).

Hydrostratigraphy

Aquifers in as many as four Cenozoic lithostratigraphic units—Quaternary unconsolidated alluvial and terrace deposits, Ogallala Formatoin, Arikaree Formation, and the White River Group or Formation—may compose the High Plains aquifer system in southeastern Wyoming (**Figure 7-2**; **Plate M**). An aquifer system consists of two or more aquifers, often vertically stacked, that are grouped together because of physical connection or sharing of similar geologic and hydrologic characteristics that are best described and studied together. Although considered part of the aquifer system or units that underlie the aquifer system, depending on location, each of the four Cenozoic lithostratigraphic units also have been traditionally defined as an individual hydrogeologic unit (aquifer or confining unit) or hydrostratigraphic unit within or below the larger High Plains aquifer system, and that usage is retained herein (last two columns in **Figure 7-2**). The individual hydrogeologic units that compose the High Plains aquifer system can be hydraulically connected to varying degrees, depending on location. Hydraulic connection between the hydrogeologic units varies locally, but regionally they are in sufficient hydraulic connection to compose a regional aquifer system (Crist, 1980; Cooley and Crist, 1981, 1994; Gutentag and Weeks, 1980; Libra et al., 1981; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984) (**Figure 7-2**). Where Quaternary unconsolidated deposits are in hydraulic connection laterally or vertically to the underlying Tertiary aquifers, the deposits are usually considered locally part of the High Plains aquifer system by most investigators (**Figure 7-2**). The Tertiary lithostratigraphic units composing the aquifer system overlie one another, although not all are present throughout southeastern Wyoming and adjacent western Nebraska (**Plate 4**) due to erosion or nondeposition. Consequently, wells completed in the High Plains aquifer system in southeastern Wyoming obtain water from one or more of these lithostratigraphic units that varies by location and well construction (some wells are completed in more than one lithostratigraphic unit).

Historically, many different combinations or groupings of the four Cenozoic lithostratigraphic units composing the High Plains aquifer system have been used by many different investigators to define various aquifers and aquifer systems at different locations in southeastern Wyoming (**Figure 7-2**). The definitions of the aquifers and aquifer systems vary due to the different Cenozoic lithostratigraphic units present at a given location, as well as different hydrogeologic characteristics of the units in the area evaluated and the interpretations of the degree of hydraulic interconnection between the units by different investigators. In many earlier studies, the degree of regional hydraulic interconnection between the different Tertiary hydrogeologic units composing the High Plains aquifer system generally went unrecognized. However, some earlier studies did recognize hydraulic connection between the units, especially in Laramie County. Lowry and Crist (1967, p. 28) noted that in areas where the Ogallala and Arikaree Formations were lithologically similar in Laramie County, "the water-bearing properties of the Ogallala and of the Arikaree are similar enough that the two formations may be considered as a [single] hydrologic unit." In addition, the investigators indirectly noted the existence of an aquifer system in Laramie County, stating that "hydraulic connection between the Tertiary formations [in Laramie County] is sufficient to permit contouring a common water table" (Lowry and Crist, 1967, p. 39). Similarly, Crist and Borchert (1972) indicated that hydraulic connection between different Tertiary lithostratigraphic units, as well between Tertiary lithostratigraphic units and extensive alluvial and

terrace deposits, in parts of southeastern Laramie County was sufficient to permit contouring a common water table.

Crist (1980) was the first investigator to formally identify and propose a regional "aquifer" or "aquifer system" composed of all the Tertiary lithostratigraphic units in southeastern Wyoming, although his study was limited to Laramie County and the aquifer system was unnamed. Additionally, he stated that part of the reason the Tertiary lithostratigraphic units were "grouped" together into an aquifer system for modeling purposes was due to difficulty differentiating the individual lithostratigraphic units throughout the county. Subsequently, Cooley and Crist (1981) and Libra et al. (1981) also recognized a regional aquifer system composed of all Tertiary lithostratigraphic units in southeastern Wyoming; the aquifer system was unnamed in Cooley and Crist (1981) but was informally defined as the "Tertiary aquifer system" in Libra et al. (1981, Figure II-5) (see "Libra et al." column in **Figure 7-2**). In fact, numerous past and current reports utilize this informal "Tertiary aquifer system" nomenclature or variations thereof ("Tertiary aquifer" or "upper Tertiary aquifer") to regionally define the High Plains aquifer system in southeastern Wyoming. Regional studies of the aquifer system in Cenozoic lithostratigraphic units in southeastern Wyoming and equivalent lithostratigraphic units in adjacent States by the USGS Regional Aquifer System Analysis (RASA) program led to formal naming and definition of the High Plains aquifer system (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984; Weeks et al., 1988). **Figure 7-2** summarizes and synthesizes these and other previous studies and attempts to unify regional aquifer and aquifer system nomenclature in southeastern Wyoming while essentially reflecting the formal definition of the regional High Plains aquifer system by the USGS RASA program (Gutentag and Weeks, 1980; Gutentag et al., 1984; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Weeks et al., 1988); however, there are some notable discrepancies and contradictions between the regional USGS definition of the aquifer system and local definitions.

Discrepancies in regional aquifer and aquifer system nomenclature (hydrostratigraphy) arise primarily as a result of different interpretations of the hydrogeologic role of the White River Group or Formation in southeastern Wyoming. The Arikaree and Ogallala Formations are defined as aquifers within the High Plains aquifer system throughout their areal extent in southeast Wyoming and adjacent States by all investigators, but the White River Group or Formation (or parts of the unit) is defined as either an aquifer or confining unit, depending upon local hydrogeologic characteristics and (or) whether the "White River" has been elevated to group rank and divided into the Brule and Chadron Formations (**Figure 7-2**). Most investigators, including the USGS RASA program, define the Brule Formation as an aquifer and part of the High Plains aquifer system only where locally permeable and (or) in hydraulic connection with the overlying Ogallala or Arikaree Formations where present; where impermeable, the formation is defined as a confining unit underlying the High Plains aquifer system. Regionally, the USGS does not consider the Chadron Formation underlying the Brule Formation to be part of the High Plains aquifer system, and the unit is classified as a confining unit, a confining unit with local aquifers, or an aquifer underlying the High Plains aquifer system (**Figure 7-2**). However, regional USGS potentiometric-surface maps group the Chadron Formation with the Brule Formation and show both units as part of the aquifer system where exposed at land surface in southeast Wyoming, primarily where the Chadron Formation is exposed at land surface in the Goshen Hole area (**Plate 4; Figure 7-2**) (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Gutentag et al., 1984; Avery and Pettijohn, 1984; Weeks et al., 1988), inferring hydraulic connection with the rest of the aquifer system (see Chadron Formation outcrop area in Goshen Hole on **Plate 4**) and somewhat contradicting the USGS RASA regional definition of the aquifer system. In addition, some local studies (most of which were conducted by the USGS and shown in **Figure 7-2**) consider the Chadron Formation (or parts of the Chadron Formation), where locally permeable, to be in hydraulic connection with adjacent members of the aquifer system in some areas in southeast Wyoming, primarily where the formation is exposed at land surface and located laterally or

vertically adjacent to other Tertiary geologic units in the Goshen Hole area (for example, Rapp et al., 1957; Borchert, 1985) or where the "White River" is not elevated to group rank and is defined as a formation (for example, Crist, 1980; Cooley and Crist, 1981). Consequently, the definition of the High Plains aquifer system proposed herein (last two columns in **Figure 7-2**) acknowledges the regional definition of the system by the USGS RASA program while also acknowledging likely local hydraulic connection of the White River Group or Formation (including the Chadron Formation) with other Cenozoic lithostratigraphic units commonly considered part of the aquifer system in parts of southeastern Wyoming.

Aquifer System Physical Characteristics

The physical characteristics of the Tertiary lithostratigraphic units composing the High Plains aquifer system are summarized in this section of the report. As noted previously, the High Plains aquifer system is composed of as many as four Cenozoic lithostratigraphic units, but the Quaternary alluvial and terrace deposit aquifers were previously described in this report.. Individual hydrogeologic units composing the High Plains aquifer system are briefly discussed below.

7.2.2.1.1 Ogallala aquifer

The Ogallala aquifer, composed of the permeable parts of the Ogallala Formation, is present in parts of four counties, but the aquifer is primarily used in Laramie County in southeastern Wyoming (**Plate 4**). In Laramie County, the aquifer is widely used as a source of water for domestic, stock, industrial, public-supply, and irrigation purposes. The relation of the Ogallala aquifer to other underlying and overlying hydrogeologic units of the High Plains aquifer system is shown in **Figure 7-2**.

Due to the heterogeneous nature of the Ogallala Formation, physical characteristics of the Ogallala aquifer are highly variable (**Plate 3**). Permeability of the Ogallala aquifer is primary (intergranular) and highly variable in southeastern Wyoming due to lithologic heterogeneity of the Ogallala Formation; transmissivity and well yields are highest where coarse-grained unconsolidated or poorly consolidated sand and gravel beds are present. Fine-grained sediments (clay, silt, and very fine sand) are very common within the Ogallala Formation, and wells completed in these sediments can be unsuccessful due to negligible or very low well yield (Knight and Morgan, 1937; Foley, 1942; Morgan, 1946; Lowry and Crist, 1967; Cooley and Crist, 1994); in addition, fine-grained sediments and zones of well-cemented sediments interbedded with coarse-grained water-bearing zones can result in widely varying hydraulic heads over short distances and locally confining or semiconfining conditions (for example, Weeks, 1964; Lowry and Crist, 1967; Cooley and Crist, 1994; Wyoming State Engineer's Office, 2008, and references therein). Hydrogeologic data describing the Ogallala aquifer in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

7.2.2.1.2 Arikaree aquifer

The Arikaree aquifer, composed of the permeable parts of the Arikaree Formation, is present in parts of as many as five counties in southeastern Wyoming, and the aquifer is present at land surface throughout much of the areal extent of the High Plains aquifer system (**Plate 4**). The relation of the Arikaree aquifer to underlying and overlying hydrogeologic units of the High Plains aquifer system is shown in **Figure 7-2**. The aquifer is primarily used as a source of water for domestic and stock use, and less often for public-supply and irrigation use (TriHydro Corporation, 2006a, b, c). The Arikaree Formation (aquifer) is absent in areas west and south of Cheyenne due to erosion or nondeposition (Denson and Bergendahl, 1961; Bart, 1974, 1975; Cooley and Crist, 1981, 1994).

Although Ogallala aquifer properties are highly variable primarily due to lithologic heterogeneity, Arikaree aquifer properties may be highly variable due to differences in the type of permeability present. As described previously, the lithology of the Arikaree Formation (excluding the basal conglomerate reported in some areas) is primarily poorly to moderately cemented, very fine-to fine-grained sandstone and generally is relatively homogenous (Morris and Babcock, 1960; Whitcomb, 1965; Stanley, 1976;

Borchert, 1976), especially when compared to the overlying Ogallala Formation (Borchert, 1976). Due to predominantly fine-grained aquifer sediments, well yields generally are small to moderate at most locations; consequently, large well yields typically are obtained by penetrating large thicknesses of the aquifer (Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Whitcomb, 1965). In most areas, permeability is primary (intergranular). Areas of high permeability and transmissivity reported in some studies may be attributable to secondary permeability development from localized fractures (Rapp et al., 1957; Morris and Babcock, 1960; Whitcomb, 1965) or concretionary zones (Whitcomb, 1965). Morris and Babcock (1960, p. 37) noted that the basal conglomerate in Platte County, where present, saturated, and poorly cemented, "may yield large quantities of water to wells;" however, the investigators also noted that "the basal conglomerate is well cemented in most places, and it is doubtful that much greater yield could be obtained from it than from the upper part of the formation." Hydrogeologic data describing the Arikaree aquifer in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

In some areas within Laramie County, lithologic and hydrologic characteristics of the Ogallala and Arikaree aquifers can be very similar. Lowry and Crist (1967, p. 28) noted that the Arikaree Formation in Laramie County could be lithologically very similar to the Ogallala Formation in places and that "it is difficult to distinguish the contact between the two formations in many wells;" the investigators also noted that in areas where both units were lithologically "similar in appearance," water-bearing properties of both units were similar enough that the two formations may be considered as a single hydrogeologic unit. Similarly, Cooley and Crist (1981) also noted the difficulty in separating the two geologic units and noted that the contact between the Ogallala and Arikaree Formations in their fence diagrams for southeastern Wyoming "generally was determined rather arbitrarily."

7.2.2.1.3 White River aquifer/confining unit

As described previously, the White River Group or Formation is defined as either an aquifer or confining unit, based on local physical characteristics. Permeability in the White River Group or Formation is due to either the presence of primary permeability in locally occurring coarse-grained deposits such as sandstone lenses and stringers and occasional conglomerates, or more commonly, secondary permeability in various mudrocks (primarily siltstone) that compose most of the unit(s). Consolidated mudrocks such as siltstone in the Brule Formation of the White River Group generally yield small volumes of water; large yields are obtained only in zones with secondary permeability development. Numerous early studies attributed locally high well yields in the White River Group or Formation [Brule Formation] in southeastern Wyoming to secondary permeability development by fractures, joints, and fissures (Knight and Morgan, 1937; Burleigh et al., 1938; Dockery, 1940; Warner, 1947; Babcock and Rapp, 1952; Rapp et al., 1953, 1957; Babcock and Bjorklund, 1956; Bjorklund, 1959; Morris and Babcock, 1960). Secondary permeability in the White River Group or Formation of southeastern Wyoming and adjacent western Nebraska has been the source of much discussion, speculation, and investigation over the years; many of the interpretations conflict with one another. Hydrogeologic data describing the White River aquifer/confining unit in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Lowry (1966) and Lowry and Crist (1967) reevaluated these earlier studies and suggested that secondary permeability was primarily due to fractures, joints, and fissures. It should be noted that most geologic and hydrogeologic studies conducted in southeastern Laramie County in the Pine Bluffs Lowlands area do not elevate the "White River" to group rank and consequently, define the unit as a formation and do not divide the upper part of the unit into the Brule Formation and the lower part into the Chadron Formation. Geologic studies and mapping immediately adjacent to the Pine Bluffs Lowlands area conducted immediately across the Wyoming-Nebraska State line show that the "White River" exposed at land surface in the area can be clearly identified as the Brule Formation (Swinehart and Diffendal, 1997, and references therein). Lowry

(1966) and Lowry and Crist (1967) observed that many of the wells with large yields previously attributed to secondary permeability development were located in valleys of major drainages; more detailed study led them to conclude that many of the wells also were likely completed in overlying Quaternary unconsolidated deposits (alluvium) composed of material derived from the "White River" [Brule Formation] rather than the formation itself. Consequently, because the large-yielding wells also were partially or completely screened in more permeable alluvium, "difficulty in differentiating the two has left the impression that the White River Formation [Brule Formation] is a much better aquifer than it really is" (Lowry, 1966, p. D219). In wells where more detailed examination showed that large yields were clearly attributable to secondary permeability and not attributable to more permeable alluvium, Lowry (1966) and Lowry and Crist (1967) concluded that piping, rather than fractures, joints, and fissures, was the process primarily responsible for the locally high secondary permeability of the White River Formation [upper part or Brule Formation]. The investigators concluded that the piping likely occurred prior to deposition of the overlying alluvium or Ogallala Formation (favorable paleotopography) and that other conditions favorable for piping to occur include favorable grain-size distribution, mineralogy, and geochemistry. Some of these conditions also were considered favorable to piping development in the Brule Formation of southeastern Wyoming in studies by Crist and Borchert (1972) and Borchert (1976).

Crist and Borchert (1972) used televiewer logs from wells to examine secondary permeability in the White River Formation [upper part or Brule Formation] in southeastern Laramie County. The investigators reported openings resembling caverns or tubes, but this interpretation also has been interpreted as asymmetric spalling of the borehole (Barrash and Morin, 1987).

Borchert (1976) used televiewer logs from wells to examine secondary permeability in the White River Formation [upper part or Brule Formation] in the Albin and La Grange areas of southeastern Wyoming. Dark regions were reported from examination of the televiewer logs, and these regions were interpreted as irregular cavities. In addition, investigators did not observe any features thought to be fractures other than possibly bedding plane fractures. Examination of the same dark regions in televiewer logs from another and more detailed study of the Brule Formation near Sidney, Nebraska, led Barrash and Morin (1987, p. 452) to conclude that these regions also could be "artifacts due to drilling disturbance and/or removal of lateral support from structurally weak, intensely fractured material."

At a study location near Sidney Draw west of Sidney, Nebraska, Barrash and Morin (1987) conducted perhaps the most detailed study of permeability in the Brule Formation. Using many different geological, geophysical, and hydrogeological methods, the investigators concluded that (1) vertical hydraulic conductivity in the unfractured part of the Brule Formation is enhanced at some locations by several types of features, including abundant pedotubules (vertical features in the rocks such as preserved animal burrows), and horizontal hydraulic conductivity in the unfractured part of the formation could be enhanced by subhorizontal parting planes; (2) acoustic televiewer logs can be used to identify zones of secondary permeability (fracture zones), and fracture zones correlate with locations of enlarged borehole diameter; and (3) televiewer images of fracture zones show fracture networks and voids (similar to some conclusions reached by Crist and Borchert, 1972, and Borchert, 1976), but the study could neither clearly support nor refute interpretation of piping for the origin and (or) nature of the fractured zones as proposed in earlier studies (Lowry, 1966; Lowry and Crist, 1967; Crist and Borchert, 1972; Borchert, 1976). Regardless of the source of permeability, all investigators conclude that permeability generally is low in the mudrocks that compose much of the White River Group or Formation unless secondary permeability is present.

Regional groundwater flow, recharge, and discharge

Groundwater in the High Plains aquifer system in southeastern Wyoming generally moves from west to east, but this pattern of flow is altered

locally by groundwater divides and by groundwater discharge to streams (**Plate 4**). In southeastern Wyoming, the altitude of the potentiometric surface declines from a high of about 6,800 ft in northwestern Laramie County to a low of about 4,100 ft in the vicinity of Torrington in the North Platte River drainage (**Plate 4**).

Recharge from the different units composing the aquifer system is from infiltration and percolation of precipitation, losses (seepage) from ephemeral and perennial streams, and infiltrating irrigation water (Dockery, 1940; Theis, 1941; Foley, 1942; Morgan, 1946; Rapp et al., 1957; Morris and Babcock, 1960; Whitcomb, 1965; Lowry and Crist, 1967; Crist and Borchert, 1972; Crist, 1980; Cooley and Crist, 1994; Nunn and Turner, 2009; Bartos et al., 2013).

Discharge from the different units composing the aquifer system is by the movement of water to seeps and springs, streams, evapotranspiration, and withdrawal from wells (Dockery, 1940; Theis, 1941; Foley, 1942; Morgan, 1946; Rapp et al., 1957; Morris and Babcock, 1960; Whitcomb, 1965; Lowry and Crist, 1967; Crist and Borchert, 1972; Crist, 1980; Cooley and Crist, 1994). Some groundwater also leaves the aquifer system in southeastern Wyoming as underflow, especially in the Quaternary unconsolidated-deposit aquifers (for example, Rapp et al., 1953; Bjorklund, 1959; Lowry and Crist, 1967).

Groundwater-flow models

Numerous groundwater-flow models of the hydrogeologic units composing the High Plains aquifer system or parts of the aquifer system in southeastern Wyoming have been constructed. Most of the groundwater-flow models were constructed in the 1970s and 1980s. Many of the groundwater-flow models were constructed using the finite-difference model of Trescott et al. (1976). This was the first "production" general purpose groundwater modeling computer code distributed by the USGS and was the precursor to MODFLOW. In this section of the report, these groundwater-flow models are identified and briefly described in order of publication. Modeling results are not described herein but are available in the identified publications.

Lines (1976) constructed a groundwater-flow model of the Arikaree aquifer in a 340-mi.^{2} area in Platte and Goshen Counties near Dwyer. In the study, the Arikaree aquifer was defined as an unconfined aquifer composed of the Arikaree and Ogallala Formations, as well as the White River Group or Formation in the western part of the study area where permeable. The Arikaree aquifer was modeled using the finite-difference model of Pinder (1970) as modified by Trescott (1973) to evaluate the effects of industrial and irrigation groundwater withdrawals on aquifer water levels and streamflow (Cottonwood Creek, North Platte River, Laramie River, and North Laramie River). The steady-state model was calibrated to hydrologic conditions in water year 1974, and predictive transient simulations were made to evaluate different groundwater withdrawal scenarios for water years 1974 to 1979.

Hoxie (1977) constructed a groundwater-flow model of the Arikaree aquifer in a 400-mi.^{2} area in central Platte County and western Goshen County near Wheatland. In the study, the Arikaree aquifer was defined as an unconfined aquifer composed of the Arikaree and Ogallala Formations, and locally the upper part of the Brule Formation where permeable, essentially using the Arikaree aquifer definition of Lines (1976). The Arikaree aquifer was modeled using the finite-difference model of Trescott et al. (1976) to evaluate the effects of industrial and irrigation groundwater withdrawals on aquifer water levels and streamflow (Laramie and North Laramie Rivers). A steady-state model was constructed and calibrated, and predictive transient simulations were made to evaluate three different combined irrigation and industrial groundwater withdrawal scenarios for water years 1969 to 1977.

Crist (1977) constructed a groundwater-flow model of the Arikaree aquifer (composed only of the Arikaree Formation) in an 800-mi.^{2} area in southern Niobrara and northern Goshen Counties near Lusk. A finite-difference model [not published at time of study but subsequently published as Trescott et al. (1976)] was used to evaluate the effects of current and future development (domestic, industrial, and agricultural use) of the aquifer, although pumpage due to then-current and potential future irrigation well development was emphasized. A steady-state model was constructed

and calibrated, and predictive transient simulations were made to evaluate irrigation and industrial groundwater withdrawals for water years 1973 to 1993.

Hoxie (1979a, 1979b) used the groundwater-flow model developed previously by Hoxie (1977) to evaluate additional groundwater-withdrawal scenarios for the Arikaree aquifer in central Platte County and western Goshen County near Wheatland. Different combined industrial and irrigation withdrawal scenarios were evaluated using the groundwater-flow model in transient mode to predict long-term groundwater level declines and streamflow depletion to the Laramie and North Laramie Rivers in the study area.

Crist (1980) constructed a groundwater-flow model of the High Plains aquifer system in Laramie County, Wyoming, and parts of adjacent Nebraska and Colorado. At the time of the study, the groundwater system comprising what is now known as the High Plains aquifer system in southeastern Wyoming and adjacent States, composed of the Ogallala and Arikaree Formations, parts of the White River Group or Formation, and local hydraulically connected Quaternary unconsolidated deposits, was unnamed by Crist and had not yet been formally named by the USGS RASA program (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984; Weeks et al., 1988). Consequently, the aquifer system was defined by Crist (1980) as "the hydrologic or groundwater system in post-Cretaceous rocks." The model was constructed to evaluate then-current (1977) groundwater-level declines, primarily in areas of large irrigation withdrawals in the eastern part of the county, and to simulate different future groundwater development scenarios. The High Plains aquifer system was modeled using the finite-difference model of Trescott et al. (1976) as modified by Hoxie (1977, p. 21-24) to account for the interaction between the aquifer and streams. A water budget was calculated assuming steady-state conditions; subsequent transient simulations for the years 1971 to 1977 also were used to calculate a water budget. Finally, the model was used to evaluate two predictive scenarios: (1) predict the results of pumping for the years 1978 to 1987, assuming the same rate as estimated for 1977 and with no additional wells added; and (2) predict the results of irrigating additional acreage in the county.

Borchert (1985) constructed a groundwater-flow model of part of the High Plains aquifer system, informally defined as the "La Grange aquifer," near La Grange primarily in southeastern Goshen County. In the study, the "La Grange aquifer" was defined as an unconfined aquifer composed of saturated, permeable Quaternary alluvium hydraulically connected to permeable parts of the White River Group (Brule and Chadron Formations). The groundwater-flow model was used to evaluate the effects of irrigation withdrawals on aquifer groundwater levels, streamflow (Horse and Bear Creeks), and Hawk Springs Reservoir water levels. The La Grange aquifer was modeled using the finite-difference model of Trescott et al. (1976) as modified by Hoxie (1977, p. 21-24) to account for the interaction between the aquifer and streams. A steady-state model was constructed and calibrated, and predictive transient simulations were made to evaluate two different scenarios for combined irrigation and industrial groundwater withdrawals for water years 1973 to 1978 and 1978 to 1980. A water budget was calculated assuming steady-state conditions. Finally, the model was used to evaluate the effects of hypothetical pumping scenarios to the aquifer in the area east of Horse Creek.

Crist (1983) constructed a groundwater-flow model of the Arikaree aquifer in a 260-mi.^{2} area in central Platte County that included the Wheatland Flats area and an adjacent area. In the study, the Arikaree aquifer was divided into an upper and lower aquifer. The upper Arikaree aquifer consisted of saturated Quaternary terrace deposits, saturated alluvium along Rock Creek-Wheatland Creek, Sybille Creek, Laramie River, and Chugwater Creek, and the upper part of the saturated Arikaree Formation to a depth of about 100 ft below land surface; the lower Arikaree aquifer consisted of the saturated Arikaree Formation below a depth of 100 ft below land surface. The groundwater-flow model was constructed to simulate hydrologic conditions in the Wheatland Flats area, including the relation between the Arikaree aquifer and adjacent streams. The Arikaree aquifer was modeled with two layers representing the upper and lower aquifer using

the finite-difference model of Trescott (1975) and Trescott et al. (1976) as modified by Hoxie (1977, p. 21-24) to account for the interaction between the aquifer and streams. A steady-state model was constructed and calibrated, and included a water budget. Finally, transient conditions were simulated for the years 1971 to 1978.

Hoxie (1983) constructed a groundwater-flow model of the Arikaree aquifer in Muleshoe Flat, a 34-mi.^{2} area in west-central Platte County west of Wheatland. In the study, the Arikaree aquifer was defined as an unconfined aquifer composed of the Arikaree and Ogallala Formations, and locally the upper part of the Brule Formation where permeable, using the Arikaree aquifer definition of Lines (1976) and Hoxie (1977, 1979a, b). The Arikaree aquifer was modeled using the finite-difference model of Trescott et al. (1976) as modified by Hoxie (1977, p. 21-24) to account for the interaction between the aquifer and streams. The groundwater-flow model was constructed to predict the temporal and spatial distribution of groundwater-level declines and streamflow depletions (Laramie River and Sybille Creek) as a result of proposed irrigation of 8,320 acres of land from 76 proposed irrigation wells within or immediately adjacent to Muleshoe Flat.

The Wyoming State Engineer's Office (1984) constructed a groundwater-flow model in cooperation with the USGS to evaluate the effects of current and potential future ranchette/subdivision development on groundwater levels in the High Plains aquifer system in a 150-mi.^{2} area immediately north of Cheyenne city limits. The short (10 pages) report does not identify the groundwater-flow model used or how the model was constructed. Four different development scenarios were simulated. Simulation results for predicted groundwater-level declines for all development scenarios were shown on four maps.

The Earth Technology Corporation (1984a, b, c, d) constructed a multilayer groundwater-flow model of the High Plains aquifer system in the vicinity of the city of Cheyenne and associated municipal well fields. Definition of the aquifer system was essentially the same as Crist (1980). Initially, the modeled area was 400 mi.^{2} (The Earth Technology Corporation, 1984a, b) but it was subsequently expanded to 540 mi.^{2} to accommodate interaction between Lodgepole Creek and the aquifer system (The Earth Technology Corporation 1984c, p. 8). The model was developed to evaluate the probable impacts to the Cheyenne municipal well fields resulting from additional water-supply demands due to the construction and deployment of the Peacekeeper missile system. Groundwater-flow model simulations were used to evaluate and optimize alternative municipal well pumpage, rehabilitation, and replacement scenarios.

As part of the USGS RASA study of the High Plains aquifer system (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984; Weeks et al., 1988), regional groundwater-flow models were constructed to describe the then-current conditions of the aquifer system (Luckey et al., 1986), as well as to simulate future conditions (Luckey et al., 1988). The groundwater-flow model of the northern part of the High Plains aquifer system included the aquifer system in southeastern Wyoming south of the Wheatland-Whalen fault system. The aquifer system, as defined in the study, was described previously in the "Hydrostratigraphy" section herein. The High Plains aquifer system was modeled using the finite-difference model of Trescott et al. (1976) as modified by Larson (1978) and the investigators. Predevelopment- and development-period models were constructed and calibrated. Different pumpage scenarios for the years 1980 to 2020 (Luckey et al., 1988) were simulated using the calibrated development-period model to predict future groundwater-level declines.

Lidstone and Anderson (1995) constructed a groundwater-flow model of the Brule aquifer (composed of the Brule Formation) for a 26.5- by 26.5-mile area centered on the city of Pine Bluffs municipal well field. The aquifer was modeled using the Prickett Lonnquist Aquifer Simulation Program (PLASM) finite-difference model (Prickett and Lonnquist, 1971). The groundwater-flow model was constructed to predict cumulative water-level declines over a 20-year period from then-current and potential future withdrawals from six public-supply wells composing the municipal well field. The groundwater-flow model was constructed to only evaluate the effects of

withdrawals from the six public-supply wells; withdrawals from non-municipal and high-production irrigation wells in the area were not incorporated into the model.

Hinckley Consulting (2009) attempted to reconstruct the Crist (1977) groundwater-flow model of the Arikaree aquifer in the vicinity of Lusk. The investigators were unable to reconstruct the model based on the data available in the report by Crist (1977). Consequently, the investigators constructed a "simplified groundwater model" using MODFLOW "to provide a semiquantitative evaluation of the future impact of irrigation pumping on groundwater levels in the study area" (Hinckley Consulting, 2009, p. 7-9). A steady-state model was constructed without pumping to establish predevelopment water levels. Subsequently, model simulations representing different pumping scenarios were used to predict corresponding Arikaree aquifer water levels in the area.

Hinckley Consulting and AMEC Earth and Environmental (2011) constructed a groundwater-flow model for a 130-mi.^{2} area of the High Plains aquifer system in the La Grange area primarily in southeastern Goshen County. The aquifer system model extent and hydrogeologic units of interest were essentially the same as modeled by Borchert (1985); consequently, the investigators reconstructed Borchert's groundwater-flow model using a modern finite-difference groundwater-flow model (MODFLOW). The investigators retained Borchert's earlier conceptualization of the aquifer system in the La Grange area—an unconfined aquifer composed of saturated, permeable Quaternary alluvium hydraulically connected to permeable parts of the White River Group (Brule Formation), identified as the La Grange aquifer. Like the earlier study by Borchert (1985), the groundwater-flow model was constructed to evaluate the effects of irrigation withdrawals on aquifer groundwater levels, streamflow (Horse and Bear Creeks), and Hawk Springs Reservoir water levels. A steady-state model was constructed and calibrated, and then predictive transient simulations were made to evaluate the effects of irrigation withdrawal scenarios. A water budget also was calculated. Finally, the investigators (Hinckley Consulting and AMEC Earth and Environmental, 2011, p. 7-5) evaluated use of the groundwater-flow model "as a tool for water-rights administration."

Currently (2013), the USGS is constructing a new groundwater-flow model of the northern High Plains aquifer system, including Wyoming (U.S. Geological Survey, 2013). The new model builds upon and refines work conducted previously as part of the USGS RASA High Plains aquifer system study (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag et al., 1984; Luckey et al., 1986; Luckey et al., 1988; Weeks et al., 1988). The model is being constructed using MODFLOW "as a tool to understand how the aquifer responds to the continuing and in some cases growing demands on the groundwater resources in the northern High Plains aquifer" (U.S. Geological Survey, 2013). Additionally, the new model can provide a water budget will be developed for the entire aquifer system.

Chemical characteristics

Chemical characteristics of the Tertiary hydrogeologic units comprising the High Plains aquifer system are described in this section of the report. All groundwater samples from the Ogallala and Arikaree aquifers, and the White River aquifer/confining unit of the High Plains aquifer system are within the Great Plains (GP) area; the GP area includes the entire areal extent of the High Plains aquifer system. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Ogallala aquifer

The chemical composition of groundwater in the Ogallala aquifer in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 120 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram C**). Most waters were

calcium-bicarbonate type. TDS concentrations were variable and indicated that most waters were fresh (97 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters were slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram C**; supplementary data tables). TDS concentrations ranged from 70 to 1,270 mg/L, with a median of 227 mg/L.

Concentrations of some characteristics and constituents in water from the Ogallala aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon (90 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, but no samples exceeded alternative MCL of 4,000 pCi/L), nitrate plus nitrite (13 percent; MCL of 10 mg/L), and lead (3 percent; USEPA MCL (action level) of 15 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (15 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), iron (6 percent; SMCL of 300 µg/L), manganese (6 percent; SMCL of 50 µg/L), sulfate (3 percent; SMCL of 250 mg/L), and pH (2 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were chloride (5 percent; WDEQ Class II standard of 100 µg/L) and sulfate (4 percent; WDEQ Class II standard of 200 mg/L). One constituent and one characteristic were measured at values greater than State of Wyoming livestock-use standards: mercury (100 percent of the two uncensored samples analyzed for the constituent; WDEQ Class III standard of 0.05 µg/L; supplementary data tables) and pH (2 percent below lower WDEQ Class III limit of 6.5). Mercury is not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics.

Arikaree aquifer

The chemical composition of groundwater in the Arikaree aquifer in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 40 wells and two test holes. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram D**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram D**; supplementary data tables). TDS concentrations ranged from 202 to 868 mg/L, with a median of 265 mg/L.

Concentrations of some characteristics and constituents in water from the Arikaree aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (71 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, whereas 14 percent exceeded alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (12 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (3 percent; SMCL of 250 mg/L), and pH (3 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. One constituent in environmental water samples was measured at concentrations greater than agricultural-use standards: sulfate (10 percent; WDEQ Class II standard of 200 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (3 percent above upper WDEQ Class III limit of 8.5).

White River aquifer/confining unit

The chemical composition of groundwater in the White River aquifer/confining unit in the

GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 49 wells and 11 springs. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram E**). TDS concentrations were variable and indicated that most waters were fresh (85 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram E**; supplementary data tables). TDS concentrations ranged from 182 to 4,540 mg/L, with a median of 337 mg/L.

Concentrations of some characteristics and constituents in water from the White River aquifer/confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (86 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, but no samples exceeded alternative MCL of 4,000 pCi/L), uranium (56 percent; MCL of 30 µg/L), nitrate (7 percent; MCL of 10 mg/L), and boron (4 percent; USEPA HAL of 6,000 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (35 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), iron (33 percent; SMCL of 300 µg/L), sulfate (17 percent; SMCL of 250 mg/L), pH (4 percent above upper SMCL limit of 8.5), fluoride (4 percent; SMCL of 2 mg/L), and chloride (2 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (46 percent of samples analyzed for the constituent; WDEQ Class II standard 8), boron (24 percent; WDEQ Class II standard of 750 µg/L), sulfate (19 percent; WDEQ Class II standard of 200 mg/L), TDS (9 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (4 percent; WDEQ Class II standard of 100 mg/L). The characteristic and constituent measured at values or concentrations greater than livestock-use standards were pH (4 percent above upper WDEQ Class III limit of 8.5) and boron (4 percent; WDEQ Class III standard of 5,000 µg/L).

Brule aquifer/confining unit

The chemical composition of groundwater in the Brule aquifer/confining unit in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 55 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram F**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E7**; **Appendix G5**, **diagram F**; supplementary data tables). TDS concentrations ranged from 214 to 676 mg/L, with a median of 357 mg/L.

Concentrations of some characteristics and constituents in water from the Brule aquifer/confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (100 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, but no samples exceeded alternative MCL of 4,000 pCi/L), nitrate plus nitrite (29 percent; MCL of 10 mg/L), boron (9 percent; USEPA HAL of 6,000), and nitrate (2 percent; MCL of 10 mg/L). Concentrations of one characteristic exceeded aesthetic standards for domestic use: TDS (9 percent; USEPA SMCL of 500 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents

in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (12 percent of samples analyzed for the constituent; WDEQ Class II standard 8) and boron (9 percent; WDEQ Class II standard of 750 µg/L). Concentrations of one constituent was measured at greater than State of Wyoming livestock-use standards: boron (9 percent; WDEQ Class III standard of 5,000 µg/L).

7.2.2.2 Chadron aquifer/confining unit

The chemical composition of groundwater in the Chadron aquifer/confining unit in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 11 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram G**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram G**; supplementary data tables). TDS concentrations ranged from 202 to 996 mg/L, with a median of 512 mg/L.

Concentrations of some characteristics and constituents in water from the Chadron aquifer/confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (64 percent; USEPA SMCL of 500 mg/L), sulfate (9 percent; SMCL of 250 mg/L), and pH (4 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (71 percent; WDEQ Class II standard of 8) and sulfate (9 percent; WDEQ Class II standard of 200 mg/L). Concentrations of one characteristic were measured at greater than State of Wyoming livestock-use standards: pH (4 percent above upper WDEQ Class III limit of 8.5).

7.2.2.3 Bug Formation

The Pliocene Bug Formation is present only in the Granite Mountains area (**Plate 1**). The Bug Formation is a "sequence of soft, pale-green, pale-brown, and white claystone, tuff, limestone, sandstone, and conglomerate" (Love, 1970, p. C100). Where present in the Granite Mountains area, the Bug Formation unconformably overlies the Split Rock Formation (**Plate J**). The "tuffaceous conglomerate at Kortes Ranch" and the Moonstone Formation overlie the Split Rock Formation where the Bug Formation is absent (**Plate J**). No information was located describing the hydrogeologic characteristics of the Bug Formation, so no further assessment of the unit was possible.

7.2.2.4 Kortes and Moonstone aquifers

The Kortes aquifer consists of the Pliocene "tuffaceous conglomerate at Kortes Ranch" (**Plate J**). Present only in the Granite Mountains area (**Plates 1, 2**), the tuffaceous conglomerate at Kortes Ranch (Love et al., 1993), recognized informally as the "Kortes formation" (informal unit, not capitalized), is composed of massive matrix- and clast-supported conglomerate, some limestone, and minor amounts of siltstone (Flanagan, 1990; Flanagan and Montagne, 1993). Deposited in alluvial fan and braided stream environments, the Kortes formation unconformably overlies the Moonstone Formation (Flanagan, 1990). Reported maximum thickness of the Kortes formation is about 1,300 ft (Flanagan and Montagne, 1993).

The Moonstone aquifer consists of the Miocene Moonstone Formation (**Plate J**). Like the Kortes formation, the Moonstone Formation is present only in the Granite Mountains area (**Plates 1, 2**). The formation is composed of shale, siltstone, sandstone, limestone, conglomerate, and reworked volcanic ash (Love, 1961; Flanagan and

Montagne, 1993). Reported thickness is 900 ft or more (Flanagan and Montagne, 1993).

Both formations are identified as aquifers herein based on a study by TriHydro Corporation (2008a, b). These investigators examined the hydrogeologic characteristics of the Kortes formation, the Moonstone Formation, and the Split Rock Formation at a location in the Split Rock syncline in the Granite Mountains. They concluded that the Kortes formation was an unconfined aquifer underlain by low-permeability strata that hydraulically isolates the aquifer from the underlying identified Moonstone aquifer, a confined aquifer composed of the Moonstone Formation. Both aquifers were shown to be hydraulically isolated from the underlying Split Rock aquifer by low permeability rocks in the upper part of Split Rock Formation. Both the Kortes and Moonstone aquifers were shown to be hydraulically connected to Sand and Deweese Creeks, both losing water to and gaining water from the streams depending upon the stream reach examined. Springs discharge locally from the Kortes aquifer along some Sand Creek terraces.

7.2.2.5 Aquifers in undifferentiated Miocene rocks and Split Rock aquifer

The physical and chemical characteristics of aquifers in undifferentiated Miocene rocks and the Split Rock aquifer in the PtRB are described in this section of the report.

Physical characteristics

Aquifers in undifferentiated Miocene rocks

The undifferentiated Miocene rocks in the Shirley Basin area consist of tuffaceous siltstone, sandstone, conglomerate, and limestone (Arikaree Formation of Denson, 1965; Harshman, 1968, 1972; Denson and Harshman, 1969). The deposits were formed by a combination of fluvial, lacustrine, and eolian processes. Most of the deposits were removed by erosion during the Quaternary period, but Denson (1965) estimated that lower and middle Miocene rocks in central Wyoming were approximately 1,000-ft thick. Harshman (1972) mapped a total thickness of as much as 180 ft in the Shirley Basin.

The upper Tertiary rocks of the Rawlins Uplift have not been mapped with a formal name. Berry (1960) noted that at one time the Browns Park Formation covered the Rawlins area, but he did not correlate the Browns Park Formation that is south of Rawlins to the Miocene and Pliocene rocks on the eastern part of the Rawlins Uplift. Berry (1960) and Welder and McGreevy (1966) considered upper Tertiary rocks of the Rawlins Uplift to be of Pliocene and Miocene age. Love and Christiansen (1985) defined the rocks as Miocene age, because of a change in the Miocene age definition. Love et al. (1993) defined the rocks as the Split Rock Formation of Miocene age. Jason Lillegraven (University of Wyoming, written commun., 2004) suggested that because of lithologic continuity, the name Browns Park Formation should be applied to these exposures. Because the name Split Rock Formation has been abandoned for these rocks in the Rawlins Uplift, this report refers to these units as undifferentiated Miocene rocks.

According to Berry (1960), the Miocene rocks of the Rawlins Uplift consist of gray to brown sandstone with lenses and beds of conglomerates. The sandstone can be tuffaceous, calcareous (ranging from calcareous sandstone to sandy limestone), and cross-bedded. The conglomerates have chert and quartz pebbles, with sporadic Precambrian cobbles. The basal conglomerate has Precambrian-, Paleozoic-, and Mesozoic-derived pebbles, cobbles, and boulders in a matrix of fine- to coarse-grained yellow-brown sandstone that is calcareous to partly tuffaceous. Berry (1960) also noted thin beds of tuffaceous light-gray limestone that had grains of chert, quartz, and feldspar, as well as some pebbles derived from Precambrian rocks. He noted a maximum thickness of approximately 624 ft.

Berry (1960, p. 25) reported that undifferentiated Miocene rocks in the Rawlins Uplift area "yield adequate water for domestic and stock use." He also reported that the rocks were "sufficiently permeable to allow free movement of water, and, because the water table generally lies at a relatively shallow depth, moderate to large amounts of water can be obtained from the thick saturated sections of the formation" (Berry, 1960, p. 25–26).

Split Rock aquifer

The Split Rock aquifer consists of the Oligocene and Miocene Split Rock Formation (**Plates J, S**). The Split Rock Formation is present primarily in the Granite Mountains area (**Plates 1, 2**).

Different names have been applied to the upper Tertiary rocks of the Granite Mountains area, leading to confusion in the nomenclature of the area (Snoke, 1993, p. 35-36). McGrew (1951, p. 56) suggested that the deposits that covered much of the area compose the Browns Park Formation. He suggested that lithologic differences between the Sweetwater Arch/ Granite Mountains area and areas to the south are attributable to different local sediment sources. Pipiringos (1955, 1961) referred to rocks of McGrew's (1951) depositional sheet that have remnants left in the north-central part of the Great Divide Basin as the Browns Park Formation.

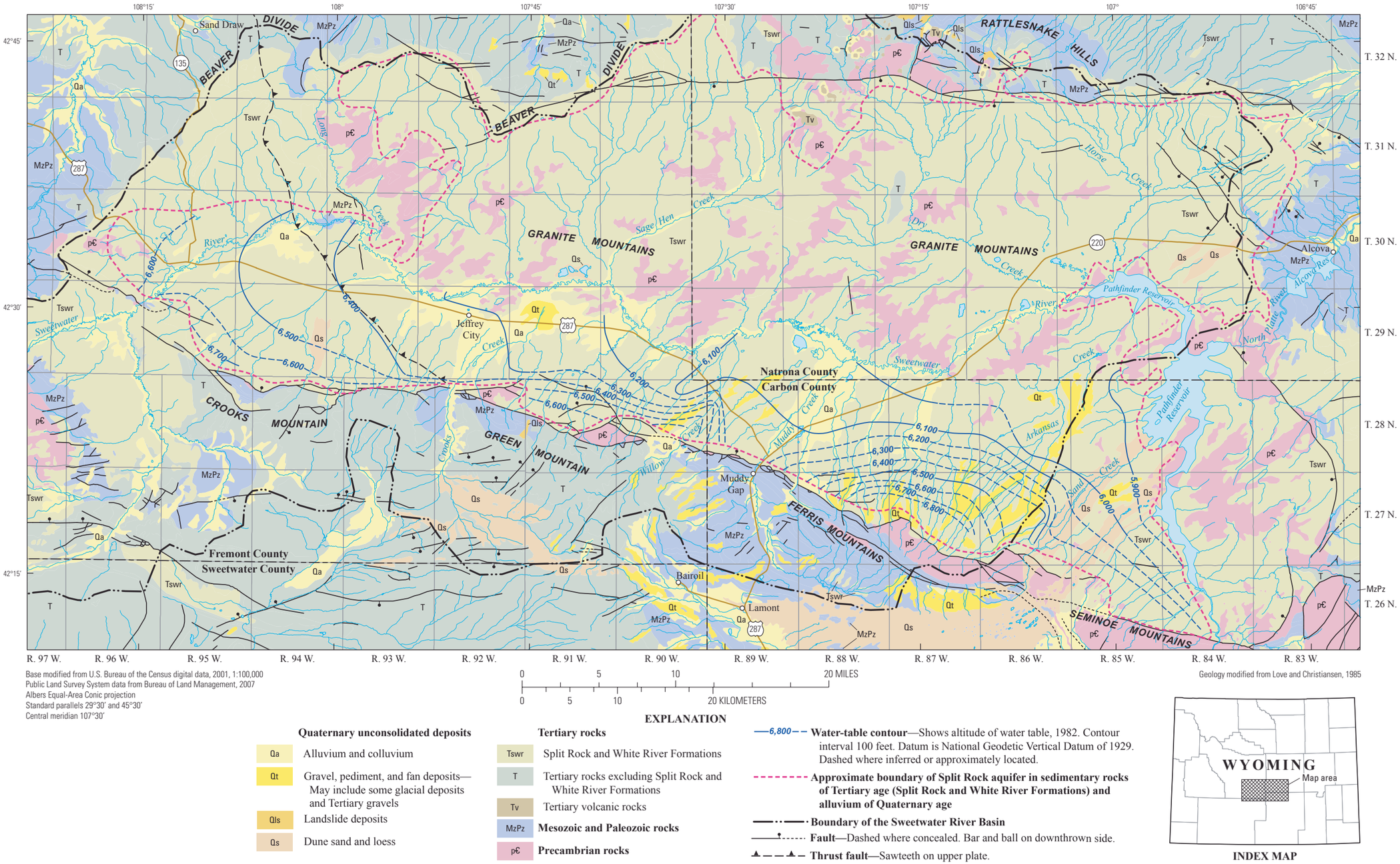
In the Granite Mountains, Love (1961) named the undifferentiated Miocene rocks the Moonstone (Pliocene-age) and the Split Rock (Miocene-age) Formations. The name Split Rock was discontinued by Denson (1965). Denson (1965) used the name Ogallala Formation (Pliocene and late Miocene-age) to replace the Moonstone Formation and the upper part of the Split Rock Formation. He also used the Arikaree Formation (middle and early Miocene-age) and the upper part of the White River Formation (late Oligocene-age) to replace the lower part of the Split Rock Formation. The Split Rock Formation of Love (1961) was mapped as Ogallala Formation by Denson and Harshman (1969) and by Lowry et al. (1973). Whitcomb and Lowry (1968) mapped the unit as Moonstone and Arikaree Formations. Love and Christiansen (1985) showed undifferentiated Miocene rocks in this area. Love et al. (1993) assigned the age of the Arikaree Formation to early Miocene and late Oligocene and the age of the Ogallala Formation to late Miocene. Jason Lillegraven (University of Wyoming, written commun., 2004) noted that the use of Ogallala and Arikaree is unjustified because of the "hundreds of miles of no exposures and involving very different kinds of lithologic characteristics" between central Wyoming and the Nebraska type localities for those names. These rocks were once again defined as the Split Rock Formation and of late Oligocene and Miocene age in the statewide Phanerozoic stratigraphic nomenclature chart (Love et al., 1993).

In the Granite Mountains area, these rocks (Split Rock Formation of Love (1961, 1970); Ogallala Formation of Denson (1965)) are gray to white fine- to medium-grained sandstone, siltstones, and tuff that contain white pumicite beds and white pumiceous limestone ledges (Denson, 1965; Whitcomb and Lowry, 1968; Richter, 1981b, Table IV-1, and references therein; Love et al., 1993). These rocks grade mountainward into sandstones, conglomerates, and gravels. The coarser facies includes a conglomerate containing chalcedony pebbles (Love, 1961). The rocks contain a large percentage of volcanic ash. The rocks probably were deposited by a combination of fluvial, lacustrine, and eolian processes. The reported thickness of the Split Rock Formation ranges from 0 to 930 ft (Richter, 1981b, Table IV-1).

In places, overlying Quaternary unconsolidated deposits and the underlying upper part of the White River Formation are in hydraulic connection with the permeable parts of the Split Rock Formation and together, the units collectively compose the Split Rock aquifer. Borchert (1977, 1987) indicated that hydraulic connection between the Split Rock and White River Formations and alluvium (where present) was sufficient to consider the units to be a single hydrogeologic unit in the Sweetwater River Basin and Granite Mountains area (**Plate J; Figure 7-3**). Similarly,

studies by the Wyoming Water Planning Program (1974) and TriHydro Corporation (2008a, b) noted that the Split Rock Formation was in hydraulic connection with the upper part of the underlying White River Formation where permeable in the Sweetwater River Basin and Granite Mountains area (**Plate J**). Groundwater flow in the Split Rock aquifer is toward the Sweetwater River and tributary canyons (Borchert, 1977, 1987; Richter, 1981b) (**Figure 7-3**).

Groundwater in the Split Rock aquifer is unconfined in most areas, but is semiconfined in some areas (Whitcomb and Lowry, 1968; Borchert, 1977, 1987; Richter, 1981b). TriHydro



Base modified from U.S. Bureau of the Census digital data, 2001, 1:100,000
Public Land Survey System data from Bureau of Land Management, 2007
Albers Equal-Area Conic projection
Standard parallels 29°30′ and 45°30′
Central meridian 107°30′

0 5 10 20 MILES

0 5 10 20 KILOMETERS

Geology modified from Love and Christiansen, 1985

EXPLANATION

Quaternary unconsolidated deposits

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits—May include some glacial deposits and Tertiary gravels
- Qls — Landslide deposits
- Qs — Dune sand and loess

Tertiary rocks

- Tswr — Split Rock and White River Formations
- T — Tertiary rocks excluding Split Rock and White River Formations
- Tv — Tertiary volcanic rocks
- MzPz — **Mesozoic and Paleozoic rocks**
- p€ — **Precambrian rocks**

—6,800— **Water-table contour**—Shows altitude of water table, 1982. Contour interval 100 feet. Datum is National Geodetic Vertical Datum of 1929. Dashed where inferred or approximately located.

Approximate boundary of Split Rock aquifer in sedimentary rocks of Tertiary age (Split Rock and White River Formations) and alluvium of Quaternary age

Boundary of the Sweetwater River Basin

Fault—Dashed where concealed. Bar and ball on downthrown side.

Thrust fault—Sawteeth on upper plate.

INDEX MAP

Figure 7-3. Water-table contours for Split Rock aquifer in Sweetwater River Basin, Wyoming (modified from Borchert, 1977, 1987).

Corporation (2008a, b) reported that the Split Rock aquifer (composed of the Split Rock Formation and the underlying upper part of the White River Formation) in the Split Rock syncline in the Granite Mountains area was confined and hydraulically isolated from the overlying Kortes and Moonstone aquifers by fine-grained rocks in the upper part of the Split Rock Formation. Whitcomb and Lowry (1968, p. 3) reported that well yields "differ greatly, depending on the permeability of the water-bearing material, the depth of penetration, and well construction," and also noted that fractures may increase aquifer permeability in some areas. Richter (1981b, Table IV-1) reported that the aquifer was permeable and productive in the Wind River Basin (WRB) and Granite Mountains area and had "good intergranular permeability and porosity." Numerous perched springs discharge small quantities of water (generally less than 20 gal/min) from the aquifer, most commonly along bedding-plane partings (Richter, 1981b).

TriHydro Corporation (2008a, b) constructed a five-layer MODFLOW groundwater flow model of the Split Rock aquifer in the Split Rock syncline in the Granite Mountains area. The model was constructed to evaluate and quantify the amount of hydraulic connection between the Split Rock aquifer and perennial streams in the region. The 400-mi.^{2} model domain included the entire Split Rock syncline area, bounded by the Sweetwater River on the north, Pathfinder Reservoir to the east, the Seminoe, Ferris, and Green Mountains on the south, and the Beaver Divide on the west. The five-layer model consisted of three aquifers (Kortes, Moonstone, and Split Rock aquifers) separated by two confining units. Steady-state and transient simulations using the calibrated numerical model were used to predict streamflow depletion to the North Platte River, Sweetwater River, and local tributaries (Sand, Dewese, and Pete Creeks) under varying Split Rock aquifer development scenarios.

For the descriptive purposes of this report, groundwater-quality samples from the late Oligocene and Miocene rocks of the Granite Mountains (Sweetwater Arch area) were grouped and identified as undifferentiated Miocene rocks. This reflects the numerous changes to the naming conventions of these rocks and historical groundwater-quality samples assigned to them. In addition, this approach acknowledges that some of these groundwater-quality samples historically assigned to previously used lithostratigraphic/hydrogeologic units may be from not only the late Oligocene and Miocene Split Rock Formation (aquifer), but also the Miocene Moonstone Formation (aquifer).

Chemical characteristics

Groundwater quality of aquifers in undifferentiated Miocene rocks is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the undifferentiated Miocene rocks in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as 23 wells and nine springs. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram A**). TDS concentrations were variable and indicated that most waters were fresh (93 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E1**; **Appendix G1**, **diagram A**; supplementary data tables). TDS concentrations ranged from 90 to 6,660 mg/L, with a median of 249 mg/L.

Concentrations of some characteristics and constituents in water from the undifferentiated Miocene rocks in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards:

radon (100 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), gross alpha radioactivity (in the one sample analyzed for this constituent; MCL of 15 pCi/L), uranium (20 percent; MCL of 30 µg/L), ammonia (12 percent; WDEQ Class I standard of 0.5 mg/L), and nitrate plus nitrite (6 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (21 percent; USEPA SMCL of 500 mg/L), sulfate (14 percent; SMCL of 250 mg/L), and chloride (4 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class II standard of 15 pCi/L), sulfate (14 percent; WDEQ Class II standard of 200 mg/L), TDS (4 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (7 percent; WDEQ Class II standard of 100 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class III standard of 15 pCi/L), TDS (4 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (4 percent; WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the undifferentiated Miocene rocks in the CBS was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations (306 and 308 mg/L) indicated that the waters were fresh.

Concentrations of some characteristics and constituents in water from the undifferentiated Miocene rocks in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of the few characteristics and constituents analyzed for, the quality of water from the undifferentiated Miocene rocks in the CBS was likely suitable for most uses. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: pH (50 percent of samples analyzed for the constituent above upper SMCL limit of 8.5), and fluoride (50 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (50 percent of samples analyzed for the constituent; WDEQ Class II standard of 8) and pH (50 percent above upper WDEQ Class II limit of 9.0). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5).

7.2.2.6 Browns Park aquifer

The physical and chemical characteristics of the Browns Park aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Browns Park aquifer consists of the Browns Park Formation (**Plate T**) and is present in the southern part of the PtRB, primarily in the Saratoga Valley area and areas to the west (**Plates 1, 2**). The Browns Park Formation contains both fluvial and eolian deposits (Love et al., 1993). Love and Christiansen (1985) showed the Miocene-age Browns Park Formation as well as the late Miocene-age North Park Formation on the statewide geologic map. Vine and Prichard (1959) used the name "North Park Formation" to describe the Miocene rocks of the Miller Hill area. No fossils were found to date the formation, and they felt it could be either the Browns Park Formation or the North Park Formation. Montagne (1991) combined the units as the Browns Park Formation because of the difficulty in establishing a mappable boundary between the two units; this reinterpretation of both units as the Browns

Park Formation was subsequently adopted in the statewide Phanerozoic chart (Love et al., 1993) and is used herein. The hydrogeologic unit described herein includes the Browns Park Formation as well as the rocks formerly assigned to the North Park Formation prior to Montagne (1991).

The Browns Park Formation has varicolored (gray, green, tan, or white) calcareous to siliceous to tuffaceous siltstones and sandstones that contain white pumicite beds, white chalcedonic and algal lacustral limestone ledges, and shaly lacustrine rocks (Powell, 1876; Hansen, 1984; Honey and Izett, 1989; Montagne, 1991). Along the uplifts, there is usually a conglomerate layer (sometimes referred to as the "basal conglomerate") primarily derived from Precambrian rocks in a cross-bedded calcareous sandy matrix (Powell, 1876; Hansen, 1984; Honey and Izett, 1989; Montagne, 1991). The formation probably was deposited by a combination of fluvial, lacustrine, and eolian processes. The Browns Park Formation is as much as 2,500-ft thick in the Saratoga Valley (Montagne, 1991).

The Browns Park aquifer is developed as a water supply for stock, domestic, and agricultural use. Sandstone and conglomerate units primarily yield water to wells completed in the aquifer. The Browns Park aquifer has been defined as a "major aquifer" (Kuhn et al., 1983) or "principal aquifer" (Richter, 1981a). In the general vicinity of the Laramie, Shirley, and Hanna Basins (including Carbon County), Richter (1981a) grouped the Browns Park Formation with other Tertiary-age formations into a single hydrogeologic unit defined as the "Tertiary aquifer." The USGS also defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Wyoming Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Variable spring discharges, well yields, and specific capacity have been reported or measured for the Browns Park aquifer. Visher (1952) reported discharges of 100, 500, and 1,300 gal/min for three springs discharging in the Pass Creek Flats area; the high spring discharges were attributed to faults. Richter (1981a) referred to the spring discharging 1,300 gal/min as the "Lake Creek Spring" and noted that the spring has been developed by the Wyoming Game and Fish Department to supply water to the Saratoga Fish Hatchery. Lowry et al. (1973, Sheet 3) reported yields of 500 to 1,000 gal/min for wells completed in Tertiary hydrogeologic units in the Laramie, Shirley, and Hanna Basins, including the Browns Park Formation in Carbon County. In addition to interstitial permeability, Lowry et al. (1973, Sheet 3) noted that high yields reported for some wells and springs were likely attributable to development of secondary permeability. Richter (1981a) reported well yields ranging from 1 to 300 gal/min, and Collentine et al. (1981) reported well yields ranging from 2.5 to 30 gal/min. In the Saratoga Valley area, wells yielding hundreds of gallons of water per minute are used for agriculture to supplement surface-water irrigation (Lenfest, 1986; Crist, 1990). Lowry et al. (1973, Sheet 3) attributed the high yields to the large saturated thickness of the formation in the area.

In the vicinity of the Miller Hill and upper Sage Creek areas south of Rawlins, medium to large springs supply much of the water supply for the city of Rawlins. Consequently, Berry (1960, p. 24) reported that "the Browns Park Formation is one of the best aquifers in the Rawlins area." He noted that one spring flowed at a rate as high as 343 gal/min. Berry (1960, p. 24) attributed all spring flows to the "basal conglomerate" of the formation and noted that the springs "maintain the base (low) flow of streams in the southern part of the area." Berry (1960, p. 24-25) speculated that the "basal conglomerate" of the Browns Park Formation in the area had much water production potential and noted that the upper part of the Browns Park Formation in the same area had the potential to "yield moderate to large supplies of water." Subsequent investigation of the "basal conglomerate" in the same area has noted little potential for development of the unit in the same Miller Hill/upper Sage Creek area. Exploratory drilling indicated that the basal conglomerate was a poorer aquifer than the overlying upper part of the Browns Park Formation in the area, as low fluid losses and lithologies encountered during drilling indicated low permeability and poor yield for development as a public water supply (James M. Montgomery, Consulting Engineers, 1983b, p. 3-11). In addition, upon review of earlier work by Vine and Prichard (1959), the investigators believed the springs actually discharge from the upper part of the Browns Park Formation, not the basal conglomerate as reported by Berry (1960).

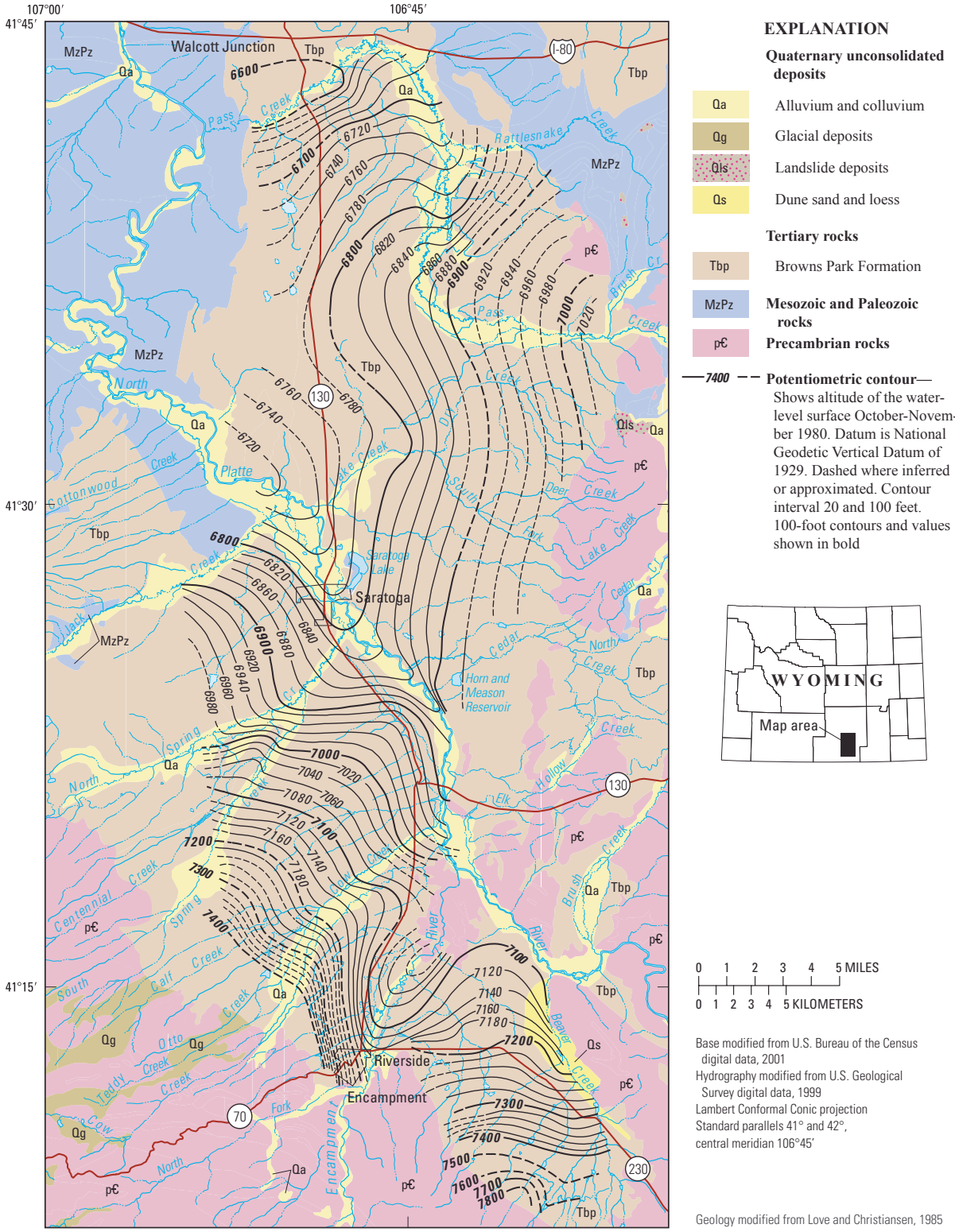


Figure 7-4. Potentiometric surface of the Browns Park aquifer in the Saratoga Valley area, Carbon County, Wyoming (modified from Crist, 1990).

These springs are still an important part of the water supply for Rawlins, but wells have been drilled into other hydrogeologic units (Cloverly and Nugget aquifers) in the Rawlins Uplift area to provide additional water for the city (James M. Montgomery, Consulting Engineers, 1983a, b; 1986a, b, and references therein).

Aquifer tests for wells completed in the Browns Park aquifer have been reported by several previous investigators. Transmissivity values for the Browns Park aquifer west of the Saratoga Valley (west of R. 86 W.) were reported to be lower than transmissivity values in the Saratoga Valley area (Collentine et al., 1981). Aquifer tests by Simons, Li, and Associates (1982a, b) and Howard, Needles, Tammen, and Bergendoff (1984) indicated that the Browns Park aquifer was confined or semiconfined at the locations examined by the investigators.

The direction of groundwater flow in the Browns Park aquifer in the Saratoga Valley area is shown on potentiometric-surface maps by Lenfest (1986, Plate 2) and Crist (1990, Plate 2). Simons, Li, and Associates (1982a) constructed a potentiometric-surface map for part of the area mapped by Lenfest (1986) and Crist (1990), including the area near Encampment and Riverside. The interpreted direction of groundwater flow is similar in all three maps. The potentiometric-surface map from Crist (1990) is reproduced herein as **Figure 7-4**. Groundwater flow is assumed to be perpendicular to the potentiometric contours and the direction of "movement generally is from the edges of the valley toward the North Platte River" (Crist, 1990, p. 9). All of these investigators noted that aquifers in Quaternary unconsolidated deposits along streams were in hydraulic connection with the Browns Park aquifer, so they mapped both units as a single aquifer in the Saratoga Valley area.

Chemical characteristics

Groundwater quality for the Browns Park aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Central Wyoming basins (south)

The chemical composition of groundwater in the Browns Park aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 59 wells, two test holes, and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram B**). TDS concentrations were variable and indicated that most waters were fresh (81 percent of samples had TDS concentration less than or equal to 999 mg/L), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram B**; supplementary data tables). TDS concentrations ranged from 153 to 3,410 mg/L, with a median of 385 mg/L.

Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (83 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), arsenic (20 percent; MCL of 10 µg/L), gross alpha radioactivity (17 percent; MCL of 15 pCi/L), fluoride (14 percent; MCL of 4 mg/L), nitrate plus nitrite (9 percent; MCL of 10 mg/L), and uranium (9 percent; MCL of 30 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: manganese (40 percent; USEPA SMCL of 50 µg/L), TDS (36 percent; SMCL of 500 mg/L), sulfate (29 percent; SMCL of 250 mg/L), aluminum (25 percent exceeded lower SMCL limit of 50 µg/L), fluoride (18 percent; SMCL of 2 mg/L), iron (8 percent; SMCL of 300 µg/L), pH (3 percent above upper SMCL limit of 8.5), and chloride (2 percent; SMCL of 250 µg/L). Aluminum is not included

in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (31 percent; WDEQ Class II standard of 200 mg/L), chloride (19 percent; WDEQ Class II standard of 100 mg/L), gross alpha radioactivity (17 percent; WDEQ Class II standard of 15 pCi/L), SAR (11 percent; WDEQ Class II standard of 8), manganese (7 percent; WDEQ Class II standard of 200 µg/L), boron (6 percent; WDEQ Class II standard of 750 µg/L), TDS (3 percent; WDEQ Class II standard of 2,000 mg/L), and pH (2 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents measured at concentrations greater than livestock-use standards were mercury (the one uncensored sample analyzed for the constituent; WDEQ Class III standard of 0.05 µg/L; supplementary data tables), gross alpha radioactivity (17 percent; WDEQ Class III standard of 15 pCi/L), and pH (3 percent above upper WDEQ Class III limit of 8.5). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics.

The chemical composition of groundwater in the Browns Park aquifer in the CBS also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (1,290 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based standards. TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs), and sulfate and chloride exceeded agricultural-use (WDEQ Class II) standards. No characteristics or constituents exceeded State of Wyoming livestock (WDEQ Class III) standards.

Vine and Prichard (1959) collected samples from 25 springs discharging from the Browns Park aquifer (referred to as North Park Formation in their report) in the Miller Hill area. The investigators were evaluating the uranium potential of the formation in the area, so all samples were analyzed for uranium. Reported uranium concentrations for the 25 springs ranged from 2 to 14 µg/L, all less than the current USEPA MCL of 30 µg/L.

Medicine Bow Mountains

The chemical composition of groundwater in the Browns Park aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E4**. TDS concentrations indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 45 to 220 mg/L, with a median of 115 mg/L.

Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed MCL, but did not exceed the alternative MCL), copper (50 percent; MCL (action level) of 1,300 µg/L), and lead (50 percent; MCL (action level) of 15 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: copper (50 percent; SMCL of 1,000 µg/L), iron (50 percent), and pH (17 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the MBM. The one constituent in environmental water samples measured at concentrations greater than agricultural-

use standards was copper (50 percent; WDEQ Class II standard of 200 µg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were copper (50 percent of samples analyzed for the constituent; WDEQ Class III standard 500 µg/L), lead (50 percent; WDEQ Class III standard of 100 µg/L), and pH (17 percent below lower WDEQ Class III limit of 6.5).

7.2.2.7 White River aquifer and confining unit (not associated with the High Plains aquifer system)

The physical and chemical characteristics of the White River aquifer and confining unit not associated with the areally extensive High Plains aquifer system in the eastern part of the PtRB are described in this section of the report.

Physical characteristics

The White River aquifer and confining unit not associated with the areally extensive High Plains aquifer system in the eastern part of the PtRB consists of the White River Formation (**Plates J, T,** and **U**). The White River Formation has small areal extent outside of the area in the PtRB associated with the High Plains aquifer system. Outside of the High Plains aquifer system, the White River Formation is present primarily in the southeastern part of Wind River Structural Basin (WRB) that falls within the PtRB, including the northeastern flank of the Granite Mountains; in the Shirley Basin area; and along the northeastern flank of the Laramie Mountains (**Plates 1, 2**). Characteristics of the White River Formation along the northeastern flank of the Laramie Mountains are the same as described in the High Plains aquifer system part of this report, so the reader is referred to that section of the report for description of the unit in that area.

In the southeastern WRB (**Plates 1, 2, Figure 3-1**), the White River Formation is composed of fine-grained sandstone with interbedded layers of tuff and bentonite, and discontinuous lenses of arkose and conglomerate (Van Houten, 1964; Whitcomb and Lowry, 1968; Richter, 1981b, Table IV-1, and references therein). Reported thickness of the White River Formation in the southeastern WRB ranges from 0 to 650 ft (Van Houten, 1964).

In the Shirley Basin and adjacent areas (**Plates 1, 2**), Harshman (1968, 1972) and Denson and Harshman (1969) described the upper part of the White River Formation as interbedded light-tan to light-brown tuffaceous (volcanic) siltstone, sandstone, and conglomerate, and the lower part of the formation as light-pink to light-tan tuffaceous siltstone and claystone. Harshman (1968, 1972) noted that the basal layer in some areas is a red, brown, or green claystone and in other areas the layer is a tuff and sandstone. The upper part is of fluvial origin and the lower part is of fluvial and lacustrine origin. The upper and lower parts are separated by a short interval of non-deposition (Harshman, 1968, 1972). The formation is as much as 850-ft thick in the Shirley Basin area.

Groundwater in the White River aquifer in the southeastern WRB is likely unconfined or semiconfined (Richter, 1981b). Richter (1981b, Table IV-1) reported that the aquifer was highly permeable and productive in the WRB and had "good intergranular permeability and porosity."

The White River Formation contains an important aquifer in the Shirley Basin, and Richter (1981a, p. 54) defined the formation as the "principal water-bearing unit in the Shirley Basin." Richter (1981a, Figure II-6, p. 20) also grouped the White River Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a more broadly defined hydrogeologic unit identified as the "Tertiary aquifer," and as a "principal aquifer." Permeability of coarse-grained lithologies was reported to be primarily intergranular. The USGS also defined the White River aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "lower Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Harshman (1972) examined the groundwater hydrology and quality of aquifers in the White River, Wind River, and Wagon Bed Formations in the Shirley Basin because of the discovery of uranium in the Wind River Formation. As part of the study, potentiometric contours were constructed showing groundwater flow in the aquifers (reproduced with modifications in **Figure 7-5**). Aquifers in all

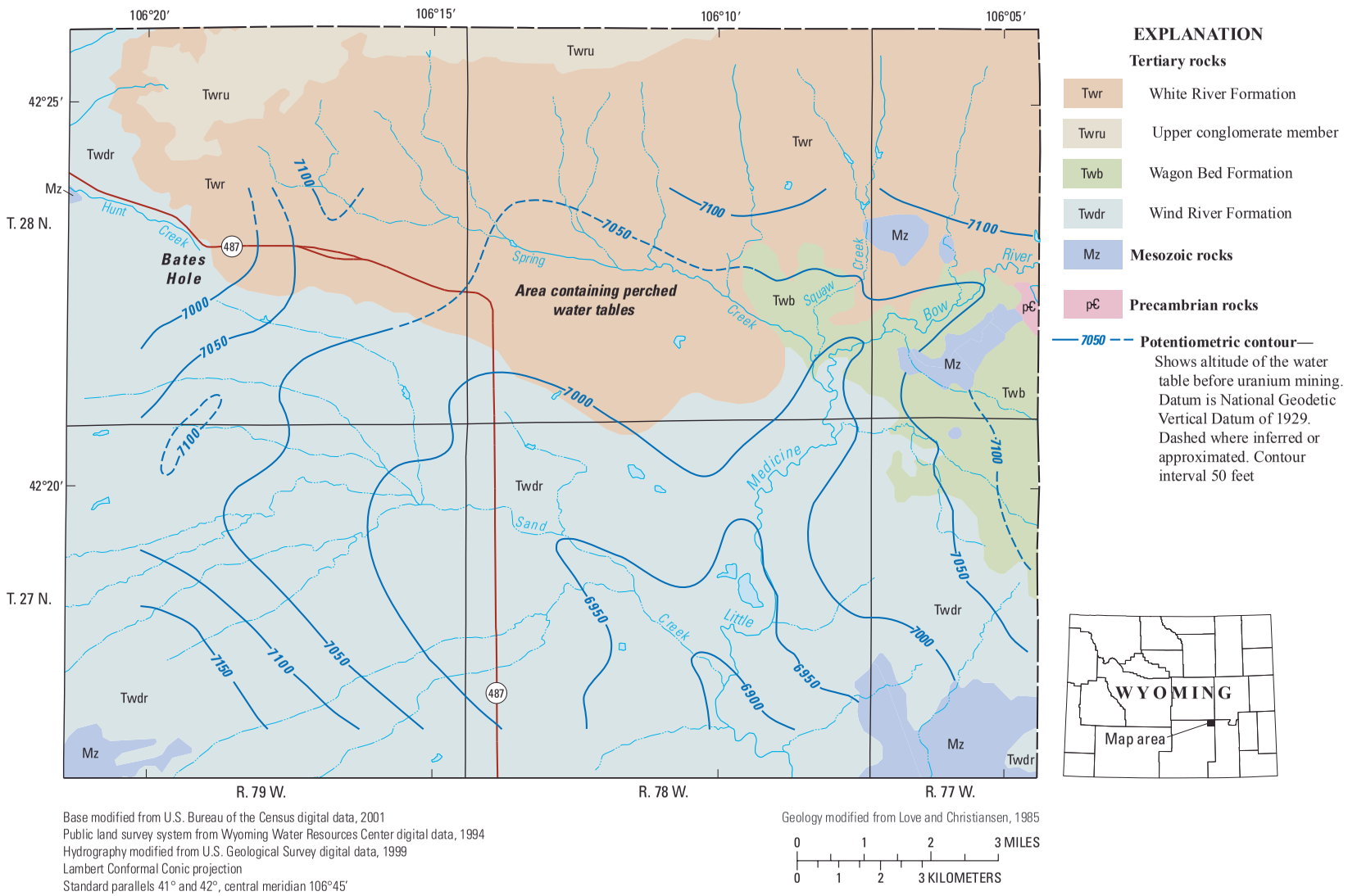


Figure 7-5. Pre-mining potentiometric surface of aquifers in Tertiary hydrogeologic units for a part of the Shirley Basin, Carbon County, Wyoming (modified from Harshman, 1972).

three formations were mapped as a single aquifer in the area, inferring hydraulic connection among the formations in the area. Harshman noted that groundwater in the White River aquifer, and in aquifers in the other formations, was unconfined and that shallow groundwater in the White River aquifer was perched (**Figure 7-5**). He also stated that Spring Creek "is fed from and flows on a perched body of water" and that "it is a gaining stream with respect to the perched water, but it may be a losing stream with respect to the main body of groundwater" (Harshman, 1972, p. 37). Harshman collected groundwater samples from eight springs discharging from the White River Formation (aquifer) to characterize waters in the area. TDS ranged from 178 to 235 mg/L, and water was classified into two groups. Groundwater samples from the first group (group 1) were collected near the base of the upper member of the White River Formation and samples from the second group (group 2) were collected near the base of the lower member. Although ionic composition was similar in both groups, and bicarbonate was the predominant anion in both groups, Harshman (1972, p. 41) noted that water from the lower member (group 2) "contains more sodium, sulfate, and uranium and somewhat less phosphate than does that from the upper member." Total radium concentrations ranged from less than 0.1 to 3.5±0.7 pCi/L, and uranium concentrations ranged from 7.8±0.8 to 52±5 µg/L. One reported uranium concentration exceeded the USEPA MCL of 30 µg/L; several other reported uranium concentrations approached but did not exceed the standard.

Chemical characteristics

Groundwater quality for the White River aquifer and confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the White River aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 216 to 397 mg/L, with a median of 282 mg/L. On the basis of the few characteristics and constituents analyzed for, the quality of water from White River aquifer in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the White River aquifer in the central Wyoming basins (south) CBS was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Summary statistics calculated for available constituents are listed in **Appendix E2**. The TDS concentrations (220 and 235 mg/L) indicated the waters were fresh (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the White River aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, most water was suitable for domestic use. The concentration of one constituent (arsenic) in one sample exceeded health-based standards for domestic use (USEPA MCL of 10 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the White River aquifer in the central Wyoming

basins (north) CBN was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and 15 springs. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram B**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E6**; **Appendix G4**, **diagram B**; supplementary data tables). TDS concentrations ranged from 69 to 400 mg/L, with a median of 191 mg/L.

Concentrations of some characteristics and constituents in water from the White River aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for domestic use. Concentrations of one characteristic exceeded aesthetic standards for domestic use (USEPA SMCL) and livestock-use (WDEQ Class III) standards: pH (12 percent below lower limit of 6.5 and 6 percent above upper limit of 8.5). Concentrations of one characteristic was measured at greater than State of Wyoming agricultural-use standards: pH (6 percent above upper WDEQ Class II limit of 9.0).

7.2.2.8 Bishop conglomerate

Little information is available describing the hydrogeologic characteristics of the Oligocene Bishop Conglomerate. Welder and McGreevy (1966, Sheet 3) and Welder (1968, Sheet 2) reported that the potential for groundwater development in the Bishop Conglomerate is not known, but is likely poor to fair. Welder (1968, Sheet 2) indicated that the deposits generally are topographically high and, consequently, probably well-drained in most areas. Little hydrogeologic information is available describing Bishop Conglomerate, but two well-yield measurements were located and are listed on **Plate 3**.

7.2.2.9 Bridger confining unit

The physical and chemical characteristics of the Bridger confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Bridger confining unit consists of the Eocene Bridger Formation and is present in the Great Divide Basin (**Plates 1, 2**). The Bridger Formation is composed of tuffaceous sandstone, claystone, lenticular marlstone, and conglomerate (Love and Christiansen, 1985, Sheet 2). Although considered an aquifer in the Green River Basin to the west, the Bridger Formation is defined as a confining unit in the Great Divide Basin (Collentine et al., 1981; Glover et al., 1998; Bartos et al., 2010, Figure 5-2). Little hydrogeologic information is available describing the Bridger confining unit in the PtRB study area, but well-yield and other hydraulic properties are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Bridger confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (252 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Bridger confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (pH above upper USEPA SMCL limit and WDEQ Class III limit of 8.5) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (pH above upper WDEQ Class II limit of 9.0 and SAR greater than WDEQ Class II standard of 8) exceeded the State of Wyoming agricultural-use standards.

7.2.2.10 Laney confining unit

The physical and chemical characteristics of the Laney confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Laney confining unit consists of the Eocene Laney Member of the Green River Formation and is present in the Great Divide Basin (**Plates 1, 2**). The Laney Member of the Green River Formation is composed of shale and marlstone (Love and Christiansen, 1985, Sheet 2). Although considered an aquifer in the Green River Basin to the west, the Laney Member of the Green River Formation was defined as a confining unit in the Great Divide Basin in previous studies (Collentine et al., 1981; Glover et al., 1998; Bartos et al., 2010, **Figure 5-2**). Little hydrogeologic information is available describing the Laney confining unit in the PtRB study area, but two well-yield measurements were located and are listed on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Laney confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (563 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Laney confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) exceeded aesthetic standards (USEPA SMCL of 500 mg/L) for domestic use. No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.11 Wagon Bed aquifer and confining unit

The physical and chemical characteristics of the Wagon Bed aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Wagon Bed aquifer and confining unit consists of the Wagon Bed Formation (Plates **J, K,** U) and is present only in a small part of the PtRB (**Plates 1, 2**). Harshman (1968, 1972) and Denson and Harshman (1969) described the formation as light-tan to light-gray, very coarse-grained sandstone that is well cemented with a clay binder, and pale-green silicified claystone. Thin-bedded freshwater limestone is present in the lower part of the formation (Harshman, 1968, 1972). Van Houten (1964) reported that the formation was deposited on warm, humid, poorly drained lowlands, flood plains, and lakes of the middle and late Eocene Epoch. The formation is as much as 160-ft thick in the PtRB.

Harshman (1972) examined the groundwater hydrology and quality of aquifers in the White River, Wagon Bed, and Wind River Formations in the Shirley Basin because of the discovery of uranium in the Wind River Formation. As part of the study, a potentiometric-surface map was constructed to show groundwater flow in the aquifers (reproduced with modifications herein as **Figure 7-5**). Aquifers in all three formations were mapped as a single aquifer in the area, inferring hydraulic connection among the formations in the area. The potentiometric contours constructed near the Little Medicine Bow River show that the stream gains flow from the Wagon Bed Formation (aquifer) in the area (**Figure 7-5**).

The Wagon Bed Formation is not permeable everywhere. Crist and Lowry (1972) considered the Wagon Bed Formation in Natrona County to be a confining unit with locally permeable zones. In the Wind River Basin and Granite Mountains area, Richter (1981b) classified the Wagon Bed Formation as a leaky confining unit (**Plate J**). Because permeability of the Wagon Bed Formation depends upon location examined, the formation is classified as an aquifer and confining unit herein (**Plates J, K,** and **U**). Hydrogeologic data describing the Wagon Bed aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Sweetwater Arch

The chemical composition of groundwater in the Wagon Bed aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations (233 and 331 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables).

On the basis of the few characteristics and constituents analyzed for, the quality of water from Wagon Bed aquifer and confining unit in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards

Central Wyoming basins (north)

The chemical composition of groundwater in the Wagon Bed aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations indicated that waters were fresh (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 213 to 310 mg/L, with a median of 310 mg/L.

On the basis of the few characteristics and constituents analyzed for, the quality of water from Wagon Bed aquifer and confining unit in the CBN was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.2.12 Ice Point Conglomerate

The Eocene Ice Point Conglomerate (**Plate J**) consists of reddish-brown conglomerate composed primarily of Paleozoic rock fragments (Love and Christiansen, 1985, Sheet 2). In the PtRB, the Ice Point Conglomerate is exposed at land surface only in a very small area on the southern Granite Mountains north of the Great Divide Basin (**Plates 1, 2**). No information describing the hydrogeologic characteristics of the unit was located, but on the basis of the description of the distribution and thickness of the conglomerate by Love (1970, p. C59), it is possible that the formation consists of little more than thin lag deposits that are likely unsaturated.

7.2.2.13 Crooks Gap Conglomerate

The physical and chemical characteristics of the Crooks Gap Conglomerate in the PtRB are described in this section of the report.

Physical characteristics

The Eocene Crooks Gap Conglomerate (**Plate J**) consists of giant granitic boulders in an arkosic sandstone matrix (Love and Christiansen, 1985, Sheet 2). In the PtRB, the Crooks Gap Conglomerate is exposed at land surface only in a very small area on the southern Granite Mountains north of the Great Divide Basin (**Plates 1, 2**). Little hydrogeologic information is available for the Crooks Gap Conglomerate likely because of very limited areal extent. One spring discharge measurement was located and is presented on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Crooks Gap Conglomerate in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (73 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Crooks Gap Conglomerate in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability

for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for domestic use. Concentrations of one constituent (mercury) exceeded State of Wyoming agriculture water-quality standards (the WDEQ Class III standard of 0.05 µg/L is more stringent than the EPA MCL of 2 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.2.2.14 Battle Spring aquifer

The physical and chemical characteristics of the Battle Spring aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Battle Spring aquifer consists of the Battle Spring Formation, which is present at or near land surface in parts of the eastern part of the Great Divide Basin in the PtRB (**Plates 1, 2**). Bradley (1961) described the Battle Spring Formation as being composed of "light gray to brown, coarse-grained to pebbly arkosic sandstone with a lesser amount of greenish gray sandy clay and mudstone; locally contains large spheroidal concretions; interfingers with the Wasatch and Green River Formations." Pipiringos (1961, p. A34-A35) suggested that the sediments composing the Battle Spring Formation were deposited in deltaic sheets associated with one of the ancient Green River lakes, and that the source of the sediment was the Granite Mountains. However, Masursky (1962, p. 10-11) and Love (1970, p. C33-C34) believed that the Battle Spring Formation mapped by Pipiringos (1955, 1961) was a mountainward fluvial facies of the main body of the Wasatch Formation and should not be considered a separate formation. Welder and McGreevy (1966, Sheet 3) reported that the Battle Spring Formation ranges in thickness from "1,000 to about 4,500 ft."

The Battle Spring Formation contains an important aquifer in the Great Divide Basin, although its extent is very limited in the PtRB. Collentine et al. (1981, Figure III-6, p. 28) combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit and defined the combined unit as a "principal aquifer" in the Great Divide and Washakie Basins. Similarly, Naftz (1996) and Glover et al. (1998) also combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit, but also included the Fort Union Formation; this unit was defined as the "Wasatch-Fort Union aquifer," and the Wasatch and Battle Spring Formations were combined and defined as a subaquifer defined as the "Wasatch zone" of the Wasatch-Fort Union aquifer. The USGS also defined the Battle Spring aquifer as a "principal aquifer" (Whitehead, 1996) and combined the aquifer with many others that comprise the "Colorado Plateaus aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Welder and McGreevy (1966) and Collentine et al. (1981) described the hydrogeologic characteristics of the Battle Spring aquifer throughout the Great Divide Basin. Welder and McGreevy (1966, Sheet 3) reported good development possibilities in the northeast part of the Great Divide Basin and noted "maximum yields of wells penetrating the entire formation might exceed 1,000 gal/min." Collentine et al. (1981, p. 52) reported that the aquifer is "capable of yielding at least 150 gal/min to water wells, though most yields generally range from 30 to 40 gal/min."

Chemical characteristics

The chemical composition of groundwater in the Battle Spring aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentrations (160 and 225 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L).

Concentrations of some characteristics and constituents in water from the Battle Spring aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for

domestic use. Concentrations of one constituent (iron) exceeded aesthetic standards for domestic use (USEPA SMCL of 300 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.15 Wind River aquifer

The physical and chemical characteristics of the Wind River aquifer in the Platte River Basin are described in this section of the report.

Physical characteristics

Present primarily in the southerneastern part of the Wind River Structural Basin that falls within the PtRB study area, the Granite Mountains area, and the Laramie and Shirley Basins, the Wind River aquifer consists of the Eocene Wind River Formation (**Plates 1, 2; Plates J, K, U**) (Bartos et al., 2012, and references therein). Thickness of the Wind River Formation in the WRB ranges from about 100 ft along mountain flanks to about 5,000 ft in the central basin (Bartos et al., 2012, and references therein). The Wind River Formation is as much as 500-ft thick in the Laramie and Shirley Basins (Richter, 1981a, Table IV-1). The Wind River Formation is composed of an interbedded sequence of claystone, shale, siltstone, and conglomerate, with lenticular beds of fine- to coarse-grained sandstone of variable thickness and areal extent; small amounts of bentonite, tuff, and limestone also may be present (Morris et al., 1959; McGreevy et al., 1969; Richter, 1981a, b). Coarser deposits may be more abundant along the basin margins because of proximity to sediment sources such as the Wind River Mountains (Whitcomb and Lowry, 1968).

In the WRB, the Wind River aquifer is underlain by the Indian Meadows confining unit or by the Fort Union aquifer, in the absence of the Eocene Indian Meadows Formation (Bartos et al., 2012, Plate II). In the Wind River Mountains, the Wind River Formation may be underlain by the Conglomerate of Roaring Fork (Bartos et al., 2012, Plate II). Where buried in the WRB, the aquifer is overlain by the Aycross-Wagon Bed confining unit [composed of the volcaniclastic Eocene Tepee Trail and Aycross Formations or siliciclastic Wagon Bed Formation (Bartos et al., 2012, Plate II)], or Quaternary unconsolidated deposits (Bartos et al., 2012, Plate II). In the Laramie and Shirley Basins, the Wind River aquifer is overlain by the Wagon Bed aquifer and confining unit (where buried) and underlain by the Fort Union or Hanna aquifers (**Plates J, U**). In the Granite Mountains area, the Wind River aquifer is overlain by the Crooks Gap Conglomerate or Wagon Bed aquifer and confining unit (defined as the Aycross-Wagon Bed confining unit in Bartos et al., 2012), depending upon which unit is present in the area examined (**Plates 1, 2; Plate J**).

The Wind River aquifer is used as a source of water for domestic, stock, irrigation, industrial, and public-supply purposes throughout the WRB (Richter, 1981a, b; Bartos et al., 2012). Many wells are installed in the Wind River aquifer in the WRB because it is present at or near land surface (crops out) throughout most of the basin. Because of limited areal extent, the aquifer is much less used in the PtRB. Where present in the Laramie and Shirley Basins, few wells are completed in the aquifer because of the sparse population in the vicinity of the aquifer outcrop. Regardless of location, most wells completed in the Wind River aquifer are for stock and domestic use because of relatively low yields and water quality that may preclude some uses without treatment (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981a, b; Bartos et al., 2012). Hydrogeologic data describing the Wind River aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate 3**. Regional groundwater flow in the Wind River aquifer in the southeastern WRB within the PtRB area is "toward the east with flow converging on Alcova and Pathfinder Reservoirs" (Richter, 1981b, p. 83).

Chemical characteristics

Groundwater quality for the Wind River aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Wind River aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E1**. On the basis of the one characteristic analyzed for, the quality of water from the Wind River aquifer in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Wind River aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples), and remaining waters were moderately saline (TDS concentrations between 3,000 and 9,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 292 to 6,450 mg/L, with a median of 980 mg/L.

Concentrations of some characteristics and constituents in water from the Wind River aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (67 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), chloride (67 percent; SMCL of 250 mg/L), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent of samples analyzed for the constituent; WDEQ Class II standard 8), chloride (67 percent; WDEQ Class II standard of 100 mg/L), sulfate (67 percent; WDEQ Class II standard of 200 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L).

Central Wyoming basins (north)

The chemical composition of groundwater in the Wind River aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 12 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations indicated that most waters were fresh (93 percent of samples), and remaining waters were slightly saline (TDS ranging from 1,000 to 2,999 mg/L) (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 82 to 1,310 mg/L, with a median of 346 mg/L.

Concentrations of some characteristics and constituents in water from the Wind River aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: aluminum (the concentration in the one sample analyzed for this constituent exceeded the SMCL limits of 50-200 µg/L), TDS (29 percent), and sulfate (29 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. The concentration of one constituent in environmental water samples exceeded

agricultural-use standards: sulfate (29 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.2.2.16 Wasatch aquifer

The physical and chemical characteristics of the Wasatch aquifer in the PtRB are described in this section of the report. Because of different geologic characteristics and hydrogeologic nomenclature in the two areas where the Wasatch Formation is present in the PtRB (Great Divide Basin and southern Powder River Basin; **Plate 1**), discussion of the Wasatch aquifer is divided into these two geographic areas.

Physical characteristics

Great Divide Basin (central Wyoming basins (south)

The Wasatch Formation, which contains the Wasatch aquifer, is composed of fluvial sediment that was deposited during the same period as the Green River Formation. In the early and middle Eocene Epoch, Lake Gosiute repeatedly expanded and contracted. Fluvial sediments of the Wasatch Formation were deposited around the margins of the lake basin in a belt that narrowed when the lake expanded and widened when the lake contracted (Bradley, 1964, p. A18).

The main body of the Wasatch Formation is present at or near land surface around the perimeter of the Washakie Basin. Masursky (1962, p. 10-11) believed that the Battle Spring Formation mapped by Pipiringos (1955, 1961) was really just a mountainward fluvial facies of the main body of the Wasatch Formation. Love (1970, p. C33-C34) supported this assessment. The Battle Spring Formation is present at or near land surface in much of the eastern part of the Great Divide Basin. The upper parts of the main body of the Wasatch Formation intertongue with tongues and members of the Green River Formation. The lower part of the main body of the Wasatch Formation predates Lake Gosiute, and underlies the Green River Formation, rather than intertonguing with it. Love and Christiansen (1985) described the main body of the Wasatch Formation in southwest Wyoming as "drab sandstone, drab to variegated claystone and siltstone; locally derived conglomerate around basin margins." Like the rest of the Wasatch Formation, the main body of the Wasatch Formation is composed of fluvial sediment deposited in the same basin occupied by Lake Gosiute. The main body of the Wasatch Formation is more than 4,000-ft thick in parts of the Green River and Washakie Basins (Roehler, 1992, p. E26–E27).

The Wasatch Formation contains an important aquifer in the Great Divide and Washakie Basins. Collentine et al. (1981, Figure III-6, p. 28) combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit and defined the combined unit as a "principal aquifer" in the Great Divide and Washakie Basins. Similarly, Naftz (1996) and Glover et al. (1998) also combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit, but also included the Fort Union Formation; this unit was defined as the "Wasatch-Fort Union aquifer" and the Wasatch and Battle Spring Formations were combined and defined as a subaquifer defined as the "Wasatch zone" of the Wasatch-Fort Union aquifer. The USGS also define the Wasatch aquifer as a "principal aquifer" (Whitehead, 1996) and combined the aquifer with many others that comprise the "Colorado Plateaus aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Individual discontinuous sandstone beds or lenses compose the Wasatch aquifer (Welder and McGreevy, 1966; Collentine et al., 1981). Welder and McGreevy (1966) reported that well yields for 90 wells in the Great Divide and Washakie Basins and surrounding areas ranged from 5 to 250 gal/min. The investigators also noted that "the maximum yield of a favorably located well might be as much as 500 gal/min" (Welder and McGreevy, 1966, Sheet 3). They also noted that artesian conditions occur in many sandstone lenses in the lower part of the formation, especially in the northwestern Great Divide Basin.

Collentine et al. (1981, Table V-1, p. 44) summarized hydrogeologic characteristics of the Wasatch aquifer throughout the Great Divide and Washakie Basins, including the eastern perimeters

of the basins in Carbon County. Reported well yields ranged from 5 to 250 gal/min, but most yields ranged from 30 to 50 gal/min.

A potentiometric surface map of the Wasatch zone of the Wasatch-Fort Union aquifer constructed by Naftz (1996) shows the direction of groundwater flow for the entire aquifer, including the eastern perimeter in western Carbon County. Based on this map, Naftz (1996) reported:

"recharge occurs in upland areas, and outcrop areas adjacent to mountain ranges, and discharge occurs along major streams and rivers of the study area. Springs in the northern part of the Great Divide-Washakie-Sand Wash Basins aquifer system serve as major discharge points; to a lesser degree, springs associated with faulting near the Little Snake River in the southern part of the basin act as discharge points."

Naftz (1996) also examined major-ion geochemistry to identify areas of recharge, discharge, and interaquifer leakage in the Wasatch zone of the Wasatch-Fort Union aquifer. He noted that recharge areas were characterized by small dissolved-solids concentrations, unique calcium and magnesium-to-sodium ratios, and small sodium and fluoride concentrations. Sulfate concentrations generally increased along projected groundwater flowpaths, and water with dissolved-solids concentrations greater than 1,500 mg/L was predominant in sodium and chloride. Examining calcium-to-chloride ratios, he concluded that ratios that exceed the local precipitation ratio are indicative of recharge areas, and ratios less than the local precipitation ratio are indicative of discharge areas.

Powder River Basin (Great Plains)

The Wasatch aquifer in the Powder River Basin consists of the Wasatch Formation (Lewis and Hotchkiss, 1981, and references therein). The Wasatch Formation is composed of fine-to coarse-grained lenticular, discontinuous sandstone beds interbedded with finer-grained sediments with low permeability such as shale, siltstone, claystone, and mudstone (Lewis and Hotchkiss, 1981, and references therein). Coal beds are locally present. The discontinuous lenticular sandstone beds are the geologic materials that primarily yield water to wells and comprise the aquifer in the Powder River Basin (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988; Bartos and Ogle, 2002, and references therein). The Wasatch aquifer overlies and is in hydraulic connection with the underlying Fort Union aquifer throughout the Powder River Basin. The aquifer is widely used for stock and domestic purposes throughout the basin. Hydrogeologic data describing the Wasatch aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater quality for the Wasatch aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Central Wyoming basins (south)

The chemical composition of groundwater in the Wasatch aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (126 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). On the basis of the few characteristics and constituents analyzed for, the quality of water from Wasatch aquifer in the CBS was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Great Plains

The chemical composition of groundwater in the Wasatch aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 wells. Summary statistics calculated for

available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were fresh (78 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 228 to 3,200 mg/L, with a median of 516 mg/L.

Concentrations of some characteristics and constituents in water from the Wasatch aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), gross alpha radioactivity (100 percent; MCL of 15 pCi/L), uranium (100 percent; MCL of 30 µg/L), lead (67 percent; MCL (action level) of 15 µg/L), and nitrate plus nitrite (11 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: ammonia (100 percent; WDEQ Class I standard of 0.5 mg/L), iron (67 percent; USEPA SMCL of 300 µg/L), manganese (67 percent; SMCL of 50 µg/L), TDS (56 percent; SMCL of 500 mg/L), sulfate (22 percent; SMCL of 250 mg/L), and pH (10 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent; WDEQ Class II standard of 15 pCi/L), manganese (67 percent; WDEQ Class II standard of 200 µg/L), selenium (33 percent; WDEQ Class II standard of 20 µg/L; supplementary data tables), boron (25 percent; WDEQ Class II standard of 750 µg/L), TDS (22 percent; WDEQ Class II standard of 2,000 mg/L), sulfate (22 percent; WDEQ Class II standard of 200 µg/L), iron (17 percent; WDEQ Class II standard of 5,000 µg/L), and SAR (11 percent; WDEQ Class II standard of 8). Selenium is not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents measured at concentrations greater than livestock-use standards were gross alpha radioactivity (100 percent; WDEQ Class III standard of 15 pCi/L) and pH (10 percent below lower WDEQ Class III limit of 6.5).

7.2.2.17 Coalmont Formation

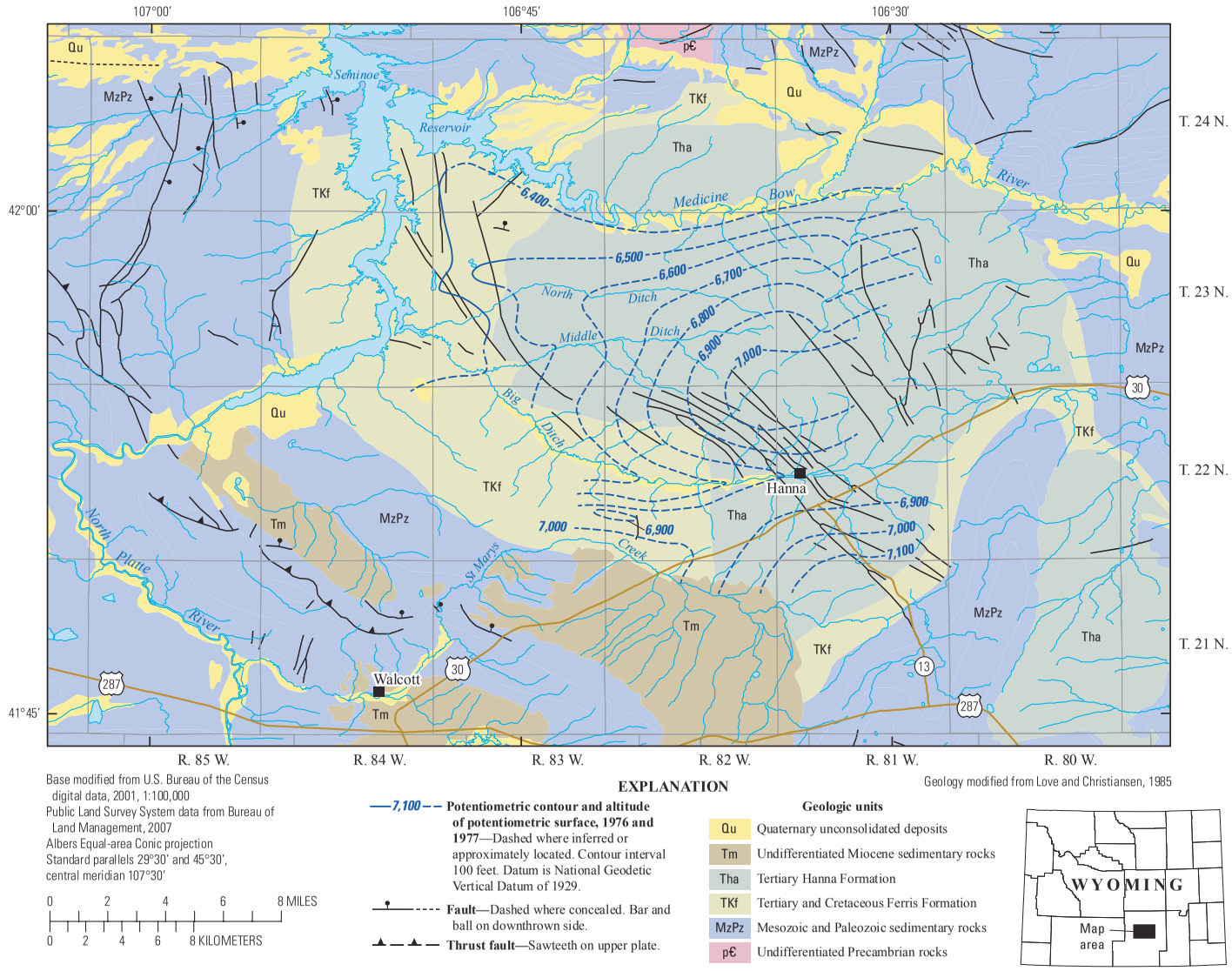
The physical and chemical characteristics of the Coalmont Formation in the PtRB are described in this section of the report.

Physical characteristics

The Coalmont Formation (**Plate T**) is present in the southern Saratoga Valley (**Plates 1, 2**). Montagne (1991, p. 16) described the unit as "brown coarse-grained arkosic sandstone with a waxy clay matrix." He also stated that the formation can be correlated to the Hanna Formation because of their similar age, structural relations, and similar lithologies. South of Saratoga Valley, the Coalmont Formation is at least 7,000-ft thick in the central part of the North Park Basin of Colorado (Montagne, 1991, p. 17). Little hydrogeologic information is available for the Coalmont Formation in the central Wyoming basins (south) (CBS) because few wells are completed in the unit because of limited areal extent.

Chemical characteristics

The chemical composition of groundwater in the Coalmont Formation in the CBS was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (136 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). On the basis of comparison of concentrations with health-based standards, the environmental water was generally suitable for domestic use. The sample



Base modified from U.S. Bureau of the Census digital data, 2001, 1:100,000
Public Land Survey System data from Bureau of Land Management, 2007
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′, central meridian 107°30′

0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

EXPLANATION

—7,100— **Potentiometric contour and altitude of potentiometric surface, 1976 and 1977**—Dashed where inferred or approximately located. Contour interval 100 feet. Datum is National Geodetic Vertical Datum of 1929.

Fault—Dashed where concealed. Bar and ball on downthrown side.

Thrust fault—Sawteeth on upper plate.

Geologic units

- Qu — Quaternary unconsolidated deposits
- Tm — Undifferentiated Miocene sedimentary rocks
- Tha — Tertiary Hanna Formation
- TKf — Tertiary and Cretaceous Ferris Formation
- MzPz — Mesozoic and Paleozoic sedimentary rocks
- p€ — Undifferentiated Precambrian rocks

Geology modified from Love and Christiansen, 1985

WYOMING
Map area

Figure 7-6. Generalized potentiometric surface for the Hanna and Ferris aquifers east of Seminoe Reservoir, Hanna Basin, south-central Wyoming (modified from Davis, 1977, Figure 1).

did exceed the proposed USEPA MCL of 300 pCi/L for radon, but did not exceed the alternative MCL of 4,000 pCi/L for radon. No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.18 Hanna aquifer

The physical and chemical characteristics of the Hanna aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Hanna aquifer consists of the Paleocene Hanna Formation (**Plate T**) and is present at or near the land surface in the Hanna, Carbon, and Laramie Basins, and the Medicine Bow Mountains (**Plates 1, 2**). The formation was named by Bowen (1918). Hyden et al. (1965) replaced the name Hanna Formation with Dutton Creek Formation in the northern part of the Laramie Basin. Gill et al. (1970) determined that the Dutton Creek Formation was one of the many coarse-grained tongues of the Hanna Formation and reinstated the name Hanna Formation.

The formation consists of alternating beds of sandstone, conglomerate, shale, and coal (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929; Gill et al., 1970; and Lowry et al., 1973). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the fine-grained sandstones are brown in color, whereas the coarse-grained sandstones are buff to grayish white. The sandstones are massive to thin-bedded, with ripple marks and cross-bedding common. They also noted that the formation was highly feldspathic. The dark-gray, yellowish, and carbonaceous shale occur in alternating beds (Bowen, 1918). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the conglomerates and conglomeratic sandstones contain pebbles of chert, granite, quartzite, sandstone, shale from the Mowry Shale, and conglomerate from the Cloverly Formation. Montagne (1991) described the Hanna Formation on Kennaday Peak and Pass Creek Basin as a conglomerate of boulders, cobbles, and pebbles, with a matrix of yellow friable medium-grained sandstone. Dobbin, Bowen, and Hoots (1929) also noted that there were locally massive conglomerates. Love and Christiansen (1985) noted the giant quartzite boulders near the Medicine Bow Mountains. Houston et al. (1968) mapped the feldspathic sandstone, arkose, carbonaceous shale, conglomeratic sandstone, and thick beds of conglomerate as Hanna and Ferris Formations undivided on the flanks of the Medicine Bow Mountains. Love and Christiansen (1985) mapped the unit as the Hanna Formation in the Medicine Bow Mountains. Gill et al. (1970) believe that the formation could be as much as 13,500-ft thick in the deepest part of the Hanna Basin.

Most wells completed in the Hanna aquifer are for stock use or for monitoring purposes near coal mines. Richter (1981a) defined the formation as a "principal aquifer" and grouped the Hanna Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the "Tertiary aquifer." The USGS also defined the Hanna aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "lower Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Hanna aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

The Hanna aquifer is composed of individual discontinuous sandstone, conglomerate, and coal beds or lenses (Lowry et al., 1973; Richter, 1981a). Permeability in the sandstones is intergranular, whereas permeability in the coalbeds is from fractures (Lowry et al., 1973; Richter, 1981a). Richter (1981a, Table IV-2, p. 53) reported that yields from "selected pumping wells completed in channel sandstones and conglomerates produce from 1 to 100 gal/min, whereas wells completed in coal seams generally produce less than 20 gal/min." In addition, Richter (1981a) reported that artesian conditions can occur locally in the Hanna aquifer with flows as large as 20 gal/min.

A generalized potentiometric-surface map constructed by Davis (1977, Figure 1) reproduced herein as **Figure 7-6** shows the direction of groundwater flow for the Hanna and Ferris aquifers between Seminoe Reservoir and the outcrop of the Hanna Formation (area in Township (T.) 22 to T.

24 North (N.), Range (R.) 83 to R. 84 West (W.)). Based on this map, groundwater in the aquifers in this area flows to the north towards the Medicine Bow River, north and south towards Big Ditch, as well as west towards Seminoe Reservoir.

Dewatering of the Hanna aquifer near coal mines in the Hanna Basin was described by Kuhn et al. (1983, p. 70–71). Examination of water levels in wells in and near dewatered mine pits indicated very complex hydrogeologic conditions. Hydraulic connection between individual permeable beds (sandstone and coal) was highly variable and unpredictable. The investigators also suggested that faulting in the area may provide hydraulic connection between individual permeable beds separated by rocks with low vertical permeability.

Chemical characteristics

The chemical composition of groundwater in the Hanna aquifer in the CBS was characterized and the quality evaluated on the basis of environmental water samples from as many as 36 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram C**). TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (49 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram C**; supplementary data tables). TDS concentrations ranged from 28 to 7,500 mg/L, with a median of 1,380 mg/L.

Concentrations of some characteristics and constituents in water from the Hanna aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (in the one filtered sample analyzed for this constituent, the concentration exceeded the WDEQ Class I standard of 0.5 mg/L), beryllium (71 percent of samples analyzed for the constituent; USEPA MCL of 4 µg/L), arsenic (4 percent; MCL of 10 µg/L), and fluoride (3 percent; MCL of 4 mg/L). Beryllium is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (80 percent; USEPA SMCL of 500 mg/L), manganese (68 percent; SMCL of 50 µg/L), sulfate (63 percent; SMCL of 250 mg/L), iron (35 percent; SMCL of 300 µg/L), aluminum (25 percent exceeded lower SMCL limit of 50 µg/L and 5 percent exceeded the upper SMCL limit of 200 µg/L), pH (17 percent above upper SMCL limit of 8.5), and fluoride (12 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were mercury (100 percent; WDEQ Class II standard of 0.05 µg/L; supplementary data tables), sulfate (69 percent; WDEQ Class II standard of 200 mg/L), SAR (50 percent; WDEQ Class II standard of 8), TDS (23 percent; WDEQ Class II standard of 2,000 mg/L), manganese (23 percent; WDEQ Class II standard of 200 µg/L), iron (9 percent; WDEQ Class II standard of 5,000 µg/L), pH (6 percent above upper WDEQ Class II limit of 9.0), chloride (6 percent; WDEQ Class II standard of 100 mg/L), and boron (3 percent; WDEQ Class II standard of 750 µg/L). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents measured at concentrations greater than livestock-use standards were pH (17 percent above upper WDEQ Class III limit of 8.5), chromium (8 percent; WDEQ Class III standard of 50 µg/L), TDS (3 percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (3 percent; WDEQ Class III standard of 3,000 µg/L).

The chemical composition of groundwater in the Hanna aquifer in the CBS also was characterized and the quality evaluated on the basis of two produced-water samples from

wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (4,690 and 5,150 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Hanna aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, sulfate, and iron exceeded aesthetic standards for domestic use (USEPA SMCLs) in both samples. TDS, chloride, and sulfate exceeded agricultural-use standards (WDEQ Class II standards) in both samples. TDS (one sample) and pH (above upper limit in both samples) exceeded State of Wyoming livestock standards (WDEQ Class III standards).

7.2.2.19 Ferris aquifer

The physical and chemical characteristics of the Ferris aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Ferris aquifer consists of the Ferris Formation (**Plate U**). The Ferris Formation is present at or near the land surface around the Hanna Basin and on the northern margin of the Carbon Basin (**Plates 1, 2**). The Ferris Formation is both Paleocene (Cenozoic) and Late Cretaceous (Mesozoic) in age and was named by Bowen (1918). The formation primarily consists of intertonguing beds of gray, brown, and yellow sandstone, light-colored, dark-gray and carbonaceous shale, and numerous thick beds of coal (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929; Gill et al., 1970; Lowry et al., 1973). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the basal part of the formation has a zone that is about 1,100-ft thick containing pockets, lenses, and thin beds of conglomerate in a massive buff to yellow sandstone. Dobbin, Bowen, and Hoots (1929) noted that the pebbles usually are less than an inch in diameter and are composed of quartzite, chert, jasper, rhyolite, and porphyry. The lower 300 ft of the formation also includes dark shale (Dobbin, Bowen, and Hoots, 1929). The formation could be as much as 6,500-ft thick.

Most wells completed in the Ferris aquifer are for stock use or for monitoring purposes near coal mines. Richter (1981a) defined the formation as a "principal aquifer" and grouped the Ferris Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the "Tertiary aquifer." The USGS also defined the Ferris aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "lower Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Ferris aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

The Ferris aquifer is composed of individual discontinuous sandstone, conglomerate, and coal beds or lenses (Lowry et al., 1973; Richter, 1981a). Permeability in the sandstones is intergranular, whereas permeability in the coalbeds is from fractures (Lowry et al., 1973; Richter, 1981a).

A generalized potentiometric-surface map constructed by Davis (1977, Figure 1) reproduced herein as **Figure 7-6** shows the direction of groundwater flow for the Hanna and Ferris aquifers between Seminoe Reservoir and the outcrop of the Hanna Formation (area in T. 22 to T. 24 N., R. 83 to R. 84 W.). Based on this map, groundwater in the aquifer in this area flows to the north towards the Medicine Bow River, north and south towards Big Ditch, as well as west towards Seminoe Reservoir.

A generalized potentiometric-surface map constructed by the Bureau of Land Management (1975, Figure 10, p. 149) reproduced herein as **Figure 7-7** shows the direction of groundwater flow for the Ferris aquifer between Seminoe Reservoir and the outcrop of the Hanna Formation

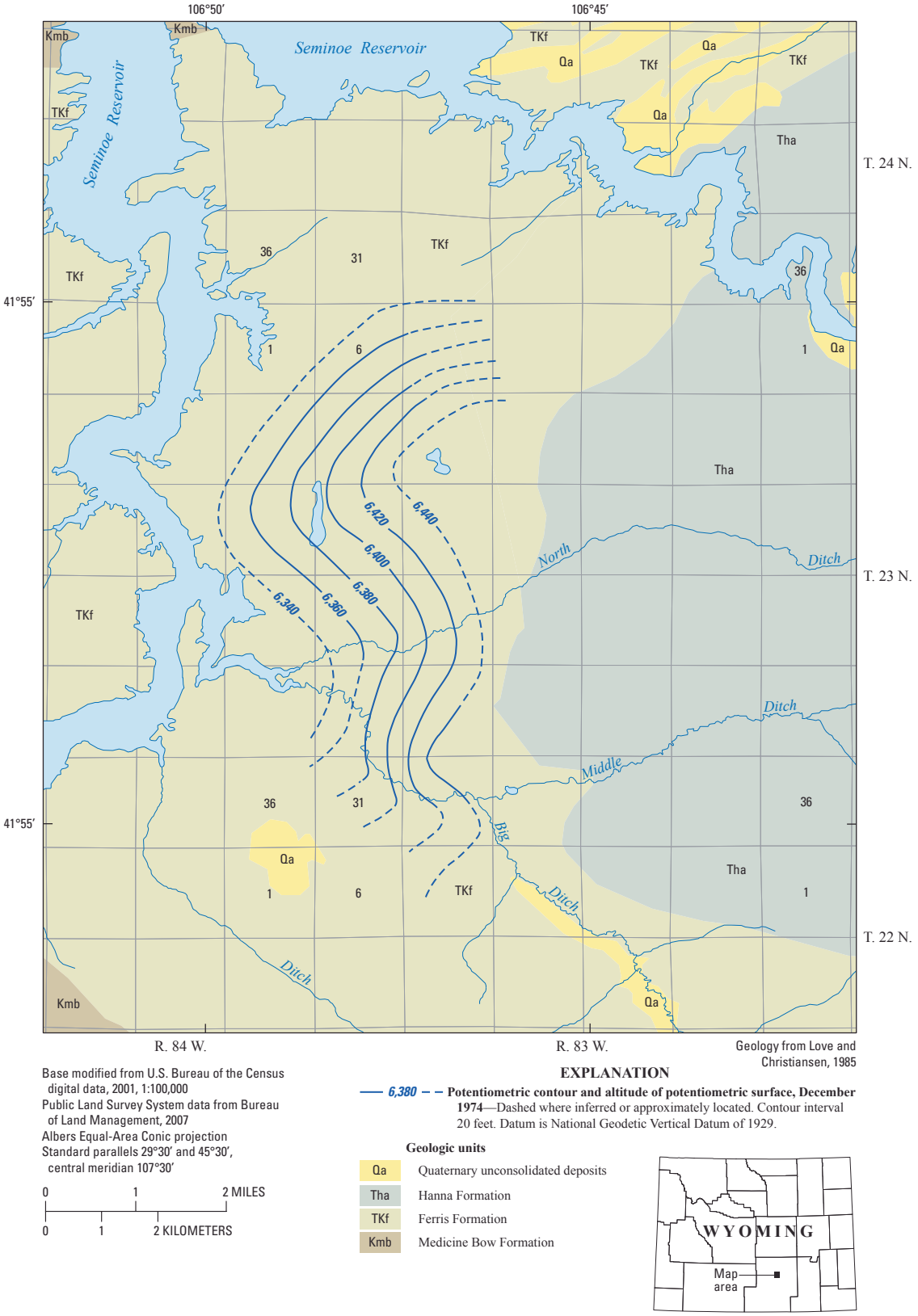


Figure 7-7. Generalized potentiometric-surface for the Ferris aquifer east of Seminoe Reservoir, northwest Hanna Basin, south-central Wyoming (modified from Bureau of Land Management, 1975).

(area in T. 22 to T. 24 N., R. 83 to R. 84 W.). Based on this map, groundwater in the aquifer in this area flows to the west towards Seminoe Reservoir.

Chemical characteristics

The chemical composition of groundwater in the Ferris aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 33 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram D**). TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (55 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram D**; supplementary data tables). TDS concentrations ranged from 614 to 8,240 mg/L, with a median of 2,770 mg/L.

Concentrations of some characteristics and constituents in water from the Ferris aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (100 percent; WDEQ Class I of 0.5 mg/L), beryllium (100 percent of samples analyzed for the constituent; USEPA MCL 4 µg/L), strontium (67 percent; USEPA HAL of 4,000 µg/L), zinc (4 percent; USEPA HAL of 2,000 µg/L); lead (5 percent; MCL (action level) of 15 µg/L), arsenic (4 percent; MCL of 10 µg/L), mercury (4 percent; MCL of 2 µg/L), selenium (4 percent; MCL of 50 µg/L), and zinc (4 percent; HAL of 2,000 µg/L). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L), sulfate (88 percent; SMCL of 250 mg/L), manganese (75 percent; SMCL of 50 µg/L), iron (50 percent; SMCL of 300 µg/L), aluminum (15 percent exceeded lower SMCL limit of 50 µg/L), fluoride (6 percent; SMCL of 2 mg/L), zinc (4 percent; SMCL of 5,000 µg/L), and pH (3 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (94 percent; WDEQ Class II standard of 200 mg/L), TDS (73 percent; WDEQ Class II standard of 2,000 mg/L), manganese (46 percent; WDEQ Class II standard of 200 µg/L), SAR (33 percent; WDEQ Class II standard of 8), vanadium (29 percent; WDEQ Class II standard of 100 µg/L), iron (17 percent; WDEQ Class II standard of 5,000 µg/L), selenium (8 percent; WDEQ Class II standard of 20 µg/L), boron (7 percent; WDEQ Class II standard of 750 µg/L), chloride (6 percent; WDEQ Class II standard of 100 mg/L), and zinc (4 percent; WDEQ Class II standard of 2,000 µg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were mercury (100 percent; WDEQ Class III standard of 0.05 µg/L), vanadium (29 percent; WDEQ Class III standard of 100 µg/L), TDS (21 percent; WDEQ Class III standard of 5,000 mg/L), sulfate (21 percent; WDEQ Class III standard of 3,000 mg/L), selenium (4 percent; WDEQ Class III standard of 50 µg/L), and pH (3 percent above upper WDEQ Class III limit of 8.5).

7.2.2.20 Fort Union aquifer

The physical and chemical characteristics of the Fort Union aquifer in the PtRB are described in this section of the report. Because of different geologic characteristics and hydrogeologic nomenclature in the two areas where the Fort Union Formation is present in the PtRB (Great Divide Basin and southern Powder River Basin; **Plate 1**), discussion of the Fort Union aquifer is divided into these two geographic areas.

Physical characteristics

Great Divide Basin [central Wyoming basins (south)]

The Fort Union aquifer consists of the Paleocene Fort Union Formation, which is present at or near land surface in the northeast corner of the Great Divide Basin, west of the town of Rawlins (**Plates 1, 2**). Harshman (1972, p. 19) speculated that the Fort Union Formation may be present in the southern part of the Shirley Basin in channels eroded into the Late Cretaceous Steele Shale. The few remnants found are sequences of varicolored soft sandy siltstones that are in part carbonaceous, but no fossils or pollen were recovered for dating. Love and Christiansen (1985) described the Fort Union Formation as "brown to gray sandstone, gray to black shale, and thin coal beds." The formation was deposited during the Paleocene Epoch and Laramide Orogeny. During this time, mountain ranges such as the Sierra Madre and the Granite Mountains were rising at the same time structural basins were subsiding. Love (1970, p. C115) reported that during the Paleocene Epoch, the Great Divide Basin was subsiding, but because the deposition of sediment derived from uplift areas filled the basin at the same rate, the surface of the basin remained at nearly the same altitude throughout the epoch. The same thing was happening in and around other basins depositing the formation during the Paleocene Epoch. The climate was warm and humid, and swamps were common. These swamps eventually would become the numerous coal deposits found in the Fort Union Formation today. Welder and McGreevy (1966, Sheet 3) reported that the thickness of the Fort Union Formation ranges from 700 to about 2,700 ft in the Great Divide and Washakie Basins.

The Fort Union Formation contains an important aquifer in the Great Divide and Washakie Basins. As noted previously, Naftz (1996) and Glover et al. (1998) combined the Wasatch, Battle Spring, and Fort Union Formations into a single hydrogeologic unit defined as the Wasatch-Fort Union aquifer. The USGS also defined the Fort Union aquifer as a "principal aquifer" (Whitehead, 1996) and combines the formation with many others that compose the "Colorado Plateaus aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Welder and McGreevy (1966) and Collentine et al. (1981) described the hydrogeologic characteristics of the Fort Union aquifer throughout the Great Divide and Washakie Basins. Collentine et al. (1981, p. 54) noted that many of the individual discontinuous sandstone beds or lenses are hydraulically isolated, although the investigators noted that sandstone and conglomerate beds in the lower part of the formation in some locations may be hydraulically connected because of fractures. Welder and McGreevy (1966, Sheet 3) reported that well yields for 11 wells ranged from 3 to 300 gal/min and noted "a well penetrating the entire formation where the sandstones are thickest might yield as much as 500 gal/min."

Most published information describing the Fort Union aquifer is from areas immediately west of the PtRB, including the Great Divide, Washakie, and Green River Basins. The reader is referred to previous publications for additional descriptions of the physical and chemical characteristics of the aquifer immediately west of the PtRB (Welder and McGreevy, 1966; Collentine et al., 1981; Taylor et al., 1986; Naftz, 1996; Mason and Miller, 2005; Bartos and Hallberg, 2010; Bartos et al., 2010).

Powder River Basin (Great Plains)

The Fort Union aquifer in the Powder River Basin consists of permeable parts of the Fort Union Formation (Lewis and Hotchkiss, 1981, and references therein). The Fort Union Formation in the Powder River Basin ranges in thickness from about 2,300 to 6,000 feet, and is divided into three members—the Tongue River, Lebo, and Tullock Members (Bartos and Ogle, 2002, and references therein). The Tongue River and Tullock Members consist of fine-to coarse-grained lenticular, discontinuous sandstone beds interbedded with finer-grained sediments with low permeability such as shale, siltstone, claystone, and mudstone (Lewis and Hotchkiss, 1981, and references therein). The Lebo Member consists primarily of shale and mudstone, interbedded with lesser amounts of sandstone, siltstone, and sparse, very thin coal beds. Coal beds are present throughout the formation and comprise some of the most laterally continuous

aquifers in the Powder River Basin (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988, and references therein).

The discontinuous lenticular sandstone beds and coal beds, primarily in the Tongue River and Tullock Members, are the actual geologic materials that primarily yield water to wells and comprise the aquifer; both members commonly are considered subaquifers in the Powder River Basin, identified as the Tongue River or Tullock aquifers (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988; Bartos and Ogle, 2002, and references therein). Because the Lebo Member is composed primarily of shale and mudstone, the unit is considered a thick confining unit between the Tongue River and Tullock aquifers. However, sandy zones within the Lebo Member are used locally to supply water for stock or domestic purposes. The Tongue River aquifer underlies and is in hydraulic connection with the overlying Wasatch aquifer throughout the Powder River Basin. Consequently, the combined Tongue River and Wasatch aquifers are commonly referred to as the "Tongue River-Wasatch aquifer" or "Wasatch-Tongue River aquifer" in the Powder River Basin (Lewis and Hotchkiss, 1981). Like the Wasatch aquifer, the Fort Union aquifer is widely used for stock and domestic purposes throughout the Powder River Basin; it is also used for public-supply purposes in parts of the basin. Hydrogeologic data describing the Fort Union aquifer, including well-yield and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater quality for the Fort Union aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Central Wyoming basins (south)

The chemical composition of groundwater in the Fort Union aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (12,400 mg/L) indicated that the water was very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L). Concentrations of some characteristics and constituents in water from the Fort Union in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but aesthetic standards for domestic use and State of Wyoming livestock-use standards were exceeded for TDS (USEPA SMCL of 500 mg/L and WDEQ Class III standard of 5,000 mg/L) and chloride (SMCL of 250 mg/L and WDEQ Class III standard of 2,000 mg/L). TDS, chloride, and sulfate in the produced-water sample exceeded State of Wyoming agricultural-use (WDEQ Class II) standards of 2,000, 100, and 200 mg/L, respectively. The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

Great Plains

The chemical composition of groundwater in the Fort Union aquifer in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (75 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 417 to 3,030 mg/L, with a median of 567 mg/L.

Concentrations of some characteristics and constituents in water from the Fort Union aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality

standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (50 percent), sulfate (25 percent), and pH (20 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (25 percent; WDEQ Class II standard of 8), TDS (25 percent), and sulfate (25 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Fort Union aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (533 mg/L) indicated that the water was fresh. The concentration of one characteristic in produced water from the Fort Union aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS exceeded aesthetic standards for domestic use. No characteristics or constituents exceeded State of Wyoming agricultural and livestock standards.

7.3 Mesozoic Hydrogeologic Units

Mesozoic hydrogeologic units are described in this section of the report. Development of most Mesozoic aquifers in the PtRB has been very limited to date (2013), except in areas where aquifers crop out and are directly exposed at land surface or at shallow depth below younger hydrogeologic units. Most wells in Mesozoic hydrogeologic units have been installed for oil and gas production, often at depths thousands of feet below land surface. Hydraulic properties, great depth, minimal precipitation and recharge, and generally poor water quality prevents extensive groundwater development of aquifers in Mesozoic hydrogeologic units.

7.3.1 Lance aquifer

The physical and chemical characteristics of the Lance aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Late Cretaceous Lance Formation, which contains the Lance aquifer, generally is present only at or near the land surface around the mountain-basin margins of the PtRB (**Plates 1, 2**). Throughout most of the PtRB, the Lance aquifer is deeply buried and, consequently, few wells are completed in the unit. In the Goshen Hole area within the Denver-Julesburg Basin, erosion of overlying Tertiary hydrogeologic units has exposed the Lance Formation at land surface (**Plates 1, 2**). The Lance Formation consists of fissile, dark-gray, brown, and carbonaceous shale, siltstone, claystone, and mudstone; interbedded brown to light brown, very fine-to fine-grained, clayey, calcareous sandstone; coal; and lignite (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981, and references therein; James M. Montgomery, Consulting Engineers, Inc., 1990c; TriHydro Corporation, 1996; Lidstone and Associates, Inc., 2003; Dahlgren Consulting, Inc., 2005). The Lance Formation was deposited in a fluvial environment. In the Denver-Julesburg Basin, reported thickness ranges from 0 to 1,500 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 8; Libra et al., 1981, Table IV-1, p. 40; Lidstone and Associates, Inc., 2003; Dahlgren Consulting, Inc., 2005). Berry

(1960) reported a thickness of as much as 4,540 ft in the Rawlins Uplift area.

In the Granite Mountains Uplift and Shirley Basin, the Lance aquifer is overlain by the Fort Union aquifer and confined from below by the Meeteetse confining unit (**Plate J**). The Lance aquifer is overlain by the White River aquifer and confining unit and underlain by the Fox Hills aquifer in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Lance aquifer is overlain by the Fort Union aquifer and underlain by the Fox Hills aquifer (**Plate S**).

The Lance Formation in the Denver-Julesburg Basin was defined as an aquifer by early investigators (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967) (**Plate M**). Libra et al. (1981) defined the Lance Formation as a "minor aquifer" in the Denver-Julesburg Basin (**Plate M**). Because of the absence of a regional confining unit, and hypothesized regional hydraulic connection, Libra et al. (1981) grouped the Lance aquifer and underlying Fox Hills aquifer together into a regional hydrogeologic unit defined as the "Lance-Fox Hills aquifer." Interpretation and use of the regional "Lance-Fox Hills aquifer" definition has been retained in subsequent studies in the Denver-Julesburg Basin (for example, Lidstone and Associates, Inc., 2003c; Dahlgren Consulting, Inc., 2005), and this interpretation tentatively is retained herein (**Plate M**).

The Lance Formation is defined as an aquifer in other parts of the PtRB. Berry (1960) considered the Lance Formation to be a potential aquifer in the Rawlins Uplift area (**Plate S**). Collentine et al. (1981) defined the Lance Formation as a "minor aquifer" and "minor water-bearing unit" in the Great Divide and Washakie Basins and Rawlins Uplift; the investigators also grouped the Late Cretaceous-age Lance Formation and Fox Hills Sandstone with formations of Tertiary age in the Great Divide and Washakie Basins area into a hydrogeologic unit defined as the "Tertiary aquifer system." The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Very fine- to fine-grained water-bearing sandstone beds in the Lance Formation compose the Lance aquifer; the sandstones are interbedded and confined by low-permeability, fine-grained rocks, locally resulting in a series of confined sandstone subaquifers (Libra et al., 1981). Confined conditions predominate, but unconfined conditions are likely in outcrop areas (Rapp et al., 1957; Libra et al., 1981). Where deeply buried, only oil and gas wells are completed in the aquifer. At shallower and economical drilling depths, wells completed in the Lance aquifer in the PtRB are used for stock or domestic purposes, primarily in the Goshen Hole area where the Lance Formation is exposed at land surface (Rapp et al., 1957; Libra et al., 1981). The aquifer is rarely used for public-supply purposes in the PtRB, primarily due to small to moderate well yields, deep burial, poor water quality for intended purposes, or large distances from towns or cities (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981). Wells completed in the aquifer supply water to the town of Rolling Hills in the southern Powder River Basin near Glenrock (James M. Montgomery, Consulting Engineers, Inc., 1990c; TriHydro Corporation, 1996). Hydrogeologic data describing the Lance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater quality for the Lance aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Central Wyoming basins (north)

The chemical composition of groundwater in the Lance aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as eight wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were fresh

(86 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 350 to 1,270 mg/L, with a median of 557 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (57 percent were greater than the USEPA SMCL of 500 mg/L) and sulfate (29 percent were greater than the SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (43 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L) and SAR (17 percent; WDEQ Class II standard of 8). No characteristics or constituents exceeded State of Wyoming livestock standards

The chemical composition of groundwater in the Lance aquifer in the CBN also was characterized and the quality evaluated on the basis of six produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,220 to 3,410 mg/L, with a median of 1,710 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), chloride (33 percent; SMCL of 250 mg/L), and pH (20 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), chloride (67 percent; WDEQ Class II standard of 100 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5).

Great Plains

The chemical composition of groundwater in the Lance aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 19 wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram H**). TDS concentrations were variable and indicated that most waters were fresh (87 percent of samples), and remaining waters were slightly saline (**Appendix E7**; **Appendix G5**, **diagram H**; supplementary data tables). TDS concentrations ranged from 264 to 1,950 mg/L, with a median of 699 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in

the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: uranium (71 percent of samples analyzed for the constituent; USEPA MCL 30 µg/L) and arsenic (20 percent; MCL of 10 µg/L; supplementary data tables). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: aluminum (the one uncensored value exceeded lower SMCL limit of 50 µg/L and 33 percent exceeded the upper SMCL limit of 200 µg/L), TDS (77 percent), fluoride (36 percent; SMCL of 2 mg/L), pH (32 percent above upper limit), manganese (25 percent; SMCL of 50 µg/L), iron (20 percent; SMCL of 300 µg/L), and sulfate (13 percent). Aluminum, arsenic, and manganese are not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (88 percent), boron (27 percent; WDEQ Class II standard of 750 µg/L), selenium (20 percent; WDEQ Class II standard of 20 µg/L), chloride (13 percent), sulfate (13 percent), and pH (5 percent above upper WDEQ Class II limit of 9.0). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (32 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Lance aquifer in the GP also was characterized and the quality evaluated on the basis of 20 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram A**). TDS concentrations were variable and indicated that most waters were slightly saline (90 percent of samples), and remaining waters were moderately saline (**Appendix F6**; **Appendix H4**, **diagram A**; supplementary data tables). TDS concentrations ranged from 1,010 to 9,620 mg/L, with a median of 1,540 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (40 percent), pH (20 percent above upper limit of 8.5 and 5 percent below lower limit of 6.5), and sulfate (10 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (80 percent), TDS (25 percent), and sulfate (20 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5 and 5 percent below lower limit of 6.5), TDS (10 percent), and chloride (10 percent; WDEQ Class III standard of 2,000 mg/L).

7.3.2 Medicine Bow aquifer

The physical and chemical characteristics of the Medicine Bow aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Medicine Bow aquifer consists of the Late Cretaceous Medicine Bow Formation (**Plate U**) and is present at or near the land surface around the margins of the Hanna, Carbon, and Laramie Basins

(**Plates 1, 2**). When the formation was named by Bowen (1918), several hundred feet of marine strata were included that have since been assigned to the Fox Hills Sandstone (Dorf, 1938, Gill et al., 1970). Hyden et al. (1965) replaced the name Medicine Bow Formation with Foote Creek Formation in the northern part of the Laramie Basin. Gill et al. (1970) determined that the rocks assigned to the Foote Creek Formation are remnants of the lower coal-bearing part of the Medicine Bow Formation.

The Medicine Bow Formation, as described by Bowen (1918) and Dobbin, Bowen, and Hoots (1929), contains yellow, gray, and carbonaceous shale, coal, and gray to brown sandstone. The investigators also described some massive white sandstone layers in the main body of the formation, and a massive, coarse-grained, friable, and easily eroded sandstone that is interbedded with beds of dark-gray shale at the top of the unit. Gill et al. (1970) noted that the Medicine Bow Formation is a thick continental unit that was deposited after the withdrawal of the Cretaceous sea. The unit is 400- to 6,200-ft thick.

Little hydrogeologic information is available for the Medicine Bow aquifer in the PtRB, and few wells are installed in the aquifer. Regardless, Richter (1981a) defined the formation as a "principal aquifer" and grouped the Medicine Bow Formation with formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the "Tertiary aquifer." Richter (1981a, Table IV-2, p. 53) reported that the formation "locally yields water to springs and shallow wells along outcrops, south flank of Freezeout Mountains." The USGS also defined the Medicine Bow aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Sandstone and coal beds compose the aquifer in the formation. Hydrogeologic data describing the Medicine Bow aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Medicine Bow aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 119 to 1,240 mg/L, with a median of 308 mg/L.

Concentrations of some characteristics and constituents in water from the Medicine Bow aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (in the one filtered sample analyzed for this constituent; USEPA SMCL of 300 µg/L), manganese (in the one sample analyzed for this constituent; USEPA SMCL of 50 µg/L), TDS (33 percent; USEPA SMCL of 500 mg/L), and sulfate (33 percent; USEPA SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Constituents in environmental water samples measured at concentrations greater than agricultural-use standards were manganese (in the one sample analyzed for this constituent; WDEQ Class II standard of 200 µg/L) and sulfate (33 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.3 Fox Hills aquifer

The physical and chemical characteristics of the Fox Hills aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Fox Hills aquifer consists of the Late Cretaceous Fox Hills Sandstone (**Plates M, S,**

U), which generally is present only at or near the land surface around the mountain-basin margins of the PtRB (**Plates 1, 2**), although little of it has been mapped in places (for example, Lowry et al., 1973). Several hundred feet of marine strata that had been assigned to the lower Medicine Bow Formation were renamed as the Fox Hills Sandstone (Dorf, 1938; Gill et al., 1970) in parts of the PtRB. It also has been mapped with the Lewis Shale in parts of the PtRB (Lowry et al., 1973; Love and Christiansen, 1985). The Fox Hills Sandstone is pale yellowish-gray, gray, yellow-brown, very fine- to medium-grained sandstone with a few beds of olive-gray to dark-gray sandy shale, thin carbonaceous shale, and thin impure beds of coal (Gill et al., 1970). In south-central Wyoming, the Fox Hills Sandstone is a shallow-marine, barrier-bar, and beach deposit that reflects the transition from the underlying Late Cretaceous marine shales (Lewis or Pierre Shales) to overlying fluvial units (Late Cretaceous Lance and Medicine Bow Formations) (Gill et al., 1970). Reported thickness of the Fox Hills Sandstone in south-central Wyoming ranges from 200 to 700 ft (Gill et al., 1970, and references therein). In the Denver-Julesburg Basin, reported thickness ranges from 0 to 550 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 9; Libra et al., 1981, Table IV-1, p. 40).

The Fox Hills aquifer is overlain by the Lance aquifer and confined from below by the Pierre confining unit in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Fox Hills aquifer is overlain by the Lance aquifer and confined from below by the Lewis confining unit (**Plate S**). The Fox Hills aquifer is overlain by the Medicine Bow aquifer and confined from below by the Lewis confining unit in the Hanna and Laramie Basins (**Plate U**).

Collentine et al. (1981) defined the Lance aquifer as a "minor aquifer" and grouped the Late Cretaceous Lance and Fox Hills Formations with Tertiary formations in the Great Divide and Washakie Basins into a hydrogeologic unit defined as the "Tertiary aquifer system." The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The Fox Hills Sandstone in the Denver-Julesburg Basin was defined as a potential aquifer (Rapp et al., 1957) or an aquifer by early investigators (Morris and Babcock, 1960; Lowry and Crist, 1967) (**Plate M**). Libra et al. (1981) defined the Fox Hills Sandstone as a "minor aquifer" in the Denver-Julesburg Basin (**Plate M**). Because of the absence of a regional confining unit, and hypothesized regional hydraulic connection, Libra et al. (1981) grouped the Fox Hills and overlying Lance aquifers together into a regional hydrogeologic unit defined as the "Lance-Fox Hills aquifer." Interpretation and use of the regional "Lance-Fox Hills aquifer" definition has been retained in subsequent studies in the Denver-Julesburg Basin (for example, Lidstone and Associates, Inc., 2003c; Dahlgren Consulting, Inc., 2005), and this interpretation tentatively is retained herein (**Plate M**).

The Fox Hills Sandstone is defined as an aquifer in other parts of the PtRB. Collentine et al. (1981) defined the Fox Hills Sandstone as a "minor aquifer" in the Great Divide and Washakie Basins and Rawlins Uplift. The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The permeable parts of the aquifer are composed primarily of very fine- to medium-grained sandstone (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981; Dahlgren Consulting, Inc., 2005). Confined conditions predominate, but unconfined conditions are likely in outcrop areas (Libra et al., 1981). The aquifer is rarely developed in the PtRB, primarily due to deep burial and availability of water from shallower aquifers, poor water quality for intended uses in places, large distances from towns or cities, and little study of hydrogeologic characteristics (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981; Sunrise Engineering and Weston Engineering, Inc., 1998, 2000). Where deeply buried, only oil and gas wells are completed in the aquifer.

Recently, a well was successfully completed in the Fox Hills aquifer to provide water for public-supply purposes to the city of Pine Bluffs in eastern Laramie County in the Denver-Julesburg Basin (Dahlgren Consulting, Inc., 2005). Adequate well yield and water quality sufficient for public-supply purposes and at an economical drilling depth suggests the aquifer has development potential in parts of the PtRB. Hydrogeologic data describing the Fox Hills aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater quality for the Fox Hills aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Central Wyoming basins (north)

The chemical composition of groundwater in the Fox Hills aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (83 percent of samples), and remaining waters were fresh (TDS concentrations less than or equal to 999 mg/L (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 943 to 2,050 mg/L, with a median of 1,390 mg/L.

Concentrations of some characteristics and constituents in water from the Fox Hills aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L) and sulfate (100 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent; WDEQ Class II standard 200 mg/L), SAR (67 percent; WDEQ Class II standard of 8), and TDS (17 percent; WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Fox Hills aquifer in the CBN also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (1,180 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Fox Hills aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. Sulfate also exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Fox Hills aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations

are listed in **Appendix E7**. On the basis of the few characteristics and constituents analyzed for, the quality of water from the Fox Hills aquifer in the PtRB was likely suitable for most uses. No characteristics or constituents in the Fox Hills aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental water sample.

7.3.4 Lewis confining unit

The physical and chemical characteristics of the Lewis confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Lewis confining unit consists of the Late Cretaceous Lewis Shale (**Plates J, S, T, U**) and is present at or near the land surface between the basins and uplifts of the PtRB (**Plates 1, 2**) and generally is deeply buried elsewhere. In the Hanna and Laramie Basins area (including Carbon Basin), the Lewis Shale is a gradational change from the overlying Fox Hills Sandstone and the underlying Almond Formation of the Mesaverde Group (**Plate U**). The middle sandy unit, called the Dad Member of the Lewis Shale (Gill et al., 1970), is a tongue of the Fox Hills Sandstone. The Lewis Shale is a dark-gray to olive-gray to buff, silty to sandy shale with dark-gray to brown carbonaceous deposits, fossiliferous limestone, siltstone concretions, very fine- to medium-grained, yellowish-gray to brown sandstones, and yellowish-gray non-resistant siltstones (Berry, 1960; Welder and McGreevy, 1966; Gill et al., 1970; Lowry et al., 1973). The Lewis Shale was deposited in a marine environment. The thickness is difficult to determine because of its gradational contact with the Fox Hills Sandstone, and because the two formations are sometimes mapped together and sometimes separately. Gill et al. (1970) measured 2,300 ft of Lewis Shale in the northwestern part of the Hanna Basin and 2,600 ft in the southeastern part of the Carbon Basin.

Because the shale that composes the predominant lithology in the Lewis Shale generally yields small quantities of water, the formation is considered to be a confining unit in the Great Divide and Washakie Basin areas (Berry, 1960; Welder and McGreevy, 1966; Collentine et al., 1981) and in the Laramie, Shirley, and Hanna Basins (Richter, 1981a). These previous investigators also noted that some sandstone lenses in the formation locally will yield small quantities of water to wells. Hydrogeologic data describing the Lewis confining unit, including well-yield and spring-discharge measurements, are summarized on **Plate 3**.

Chemical characteristics

Central Wyoming Basins (south)

The chemical composition of groundwater in the Lewis confining unit in the CBS was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (75 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations in the environmental water samples ranged from 1,340 to 9,180 mg/L, with a median of 1,990 mg/L.

Concentrations of some characteristics and constituents in water from the Lewis confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), strontium (in the one sample analyzed for this constituent; USEPA HAL of 4,000 µg/L) and uranium (in the one sample analyzed for this constituent; USEPA MCL of 30 µg/L).

Concentrations of one characteristic and three constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L), manganese (in the one sample analyzed for this constituent; USEPA SMCL of 50 µg/L), sulfate (100 percent; USEPA SMCL of 250 mg/L), and fluoride (25 percent; USEPA SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), SAR (50 percent; WDEQ Class II standard of 8), and TDS (50 percent; WDEQ Class II standard of 2,000 mg/L). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (25 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (25 percent; WDEQ Class II standard of 3,000 mg/L).

The chemical composition of groundwater in the Lewis confining unit in the CBS also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. TDS concentrations indicated that waters were slightly saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,210 to 2,060 mg/L, with a median of 1,580 mg/L.

Concentrations of some characteristics and constituents in water from the Lewis confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (67 percent; SMCL of 250 mg/L), sulfate (33 percent), and pH (33 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent; WDEQ Class II standard100 mg/L), TDS (33 percent), and sulfate (33 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper WDEQ Class III limit of 8.5).

Great Plains

The chemical composition of groundwater in the Lewis confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (8,450 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Lewis confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards.

7.3.5 Pierre confining unit

The physical and chemical characteristics of the Pierre confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Pierre confining unit consists of the thick Late Cretaceous Pierre Shale (**Plate M**) and generally is deeply buried in the Denver-Julesburg Basin (**Plates 1, 2**). The Pierre Shale is a dark-gray shale with interbedded thin to moderately thick beds of sandstone; thickness ranges from 0 to 5,700 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 9; Libra et al., 1981, Table IV-1, p. 40; Dahlgren Consulting, Inc., 2005). The Pierre Shale was deposited in a marine environment.

Because shale is the predominant lithology in the Pierre Shale, and shale generally yields small quantities of water, the formation generally is considered to be a thick regional confining unit in the Denver-Julesburg Basin (Libra et al., 1981) (**Plate M**). Sandstone lenses in the unit will locally yield small quantities of water to wells in some areas and can be considered "discontinuous minor aquifers" (Libra et al., 1981, Table IV-1, p. 40). Hydrogeologic data describing the Pierre confining unit, including well-yield measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Pierre confining unit in the GP was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (379 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Pierre confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (pH above upper limit) exceeded aesthetic standards for domestic use (USEPA SMCL of 8.5) and State of Wyoming livestock-use (WDEQ Class III standard of 8.5) and agricultural-use (WDEQ Class II standard of 9.0) standards.

7.3.6 Mesaverde aquifer

The physical and chemical characteristics of the Mesaverde aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Mesaverde aquifer consists of the Late Cretaceous Mesaverde Group or Formation (**Plates J, S, T, U**) and is present at or near the land surface between the basins and uplifts of the PtRB (**Plates 1, 2**). In much of the PtRB, the Mesaverde Group or Formation represents a gradational change from the underlying Steele and Cody Shales to the overlying Lewis Shale (**Plates J, S, T, U**). In parts of the PtRB, much of the Mesaverde Formation was eroded prior to and following the deposition of the Teapot Sandstone Member (Reynolds, 1966, 1967). Reynolds (1966, 1967) indicated that the Mesaverde Formation was completely eroded from some areas in the PtRB. In other areas, rocks of the Mesaverde Group, as assigned by Gill et al. (1970), consist of the Almond Formation, Pine Ridge Sandstone (Teapot Sandstone Member equivalent), Allen Ridge Formation, Rock River Formation, and Haystack Mountains Formation (Love et al., 1993; **Plate U**). Previous studies (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929) referred to an upper sequence (sandstone, shale, carbonaceous shale, and coal), a middle sequence (sandstone, carbonaceous shale, and coal of fresh-and brackish-water origin), and a lower sequence (marine sandstone and shale).

The undifferentiated Mesaverde Formation present in some areas is described as light gray to brown, very fine-to medium-grained sandstone interbedded with gray to dark-gray shale, siltstone, lenses of carbonaceous shale, thin lenses of lignite, and thick sections of coal (Berry, 1960; Reynolds, 1966; Welder and McGreevy, 1966). Reynolds (1966, 1967) described the Teapot Sandstone Member as a lower light-gray to white sandstone and an upper sequence of reddish-brown to white weathered carbonaceous siltstone and sandstone beds. Reynolds (1966) indicated that

the Mesaverde Formation is of littoral, shallow marine, brackish, and non-marine origins. Berry (1960) and Welder and McGreevy (1966) gave a maximum thickness of 2,800 ft.

The Almond Formation of the Mesaverde Group intertongues with the overlying Lewis Shale (**Plates S, U**) (Gill et al., 1970; Love et al., 1993). The Almond Coal Group was described by Schultz (1909) and elevated to formation rank by Sears (1926). The Almond Formation is described as interbedded sandstone, siltstone, shale, and coal (Welder and McGreevy, 1966; Gill et al., 1970). The very fine-grained sandstone is white to pale yellowish-gray to dusky yellow, and it weathers to brown (Schultz, 1909; Gill et al., 1970). The shales are dark-gray to olive-gray or brownish-gray to brownish-black and carbonaceous to coaly (Schultz, 1909; Gill et al., 1970). Gill et al. (1970) indicated that the lower part is fluvial sandstone, shale, and coal, whereas the upper part is shallow-water marine sandstone, lagoonal or brackish-water rocks, and marine shale (tongues of Lewis Shale). The Almond Formation ranges from 0- to 600-ft thick.

The Pine Ridge Sandstone of the Mesaverde Group (**Plates S, U**) is a white to pale yellowish-gray to light-gray, fine- to medium-grained, non-marine sandstone (Dobbin, Hoots, et al., 1929; Gill et al., 1970). Gill et al. (1970) indicate that this formation is equivalent to the Teapot Sandstone Member of the Mesaverde Formation. The Pine Ridge Sandstone also contains beds of light-gray carbonaceous shale, gray sandy shale, and beds of impure coal (Dobbin, Hoots, et al., 1929; Gill et al., 1970). Gill et al. (1970) noted that this is a fluvial deposit during the eastward regressive tongue of the Mesaverde Group, with a thickness of 60 to 450 ft.

The Allen Ridge Formation of the Mesaverde Group intertongues with the Rock River Formation in the northwestern Laramie Basin (**Plate U**). It consists of an upper unit of reddish-brown carbonaceous shale, shallow-water marine sandstone, and dark brownish-gray ironstone-bearing shale (Bergstrom, 1959; Gill et al., 1970). The middle unit consists of fossiliferous shale, siltstone, and sandstone (Bergstrom, 1959; Gill et al., 1970). The lower unit consists of brown to rusty-brown fluvial sandstone and shale that contains many beds of carbonaceous shale, very little coal, and numerous ironstone concretions (Bergstrom, 1959; Gill et al., 1970). Gill et al. (1970) noted that the unit is entirely non-marine in the Great Divide and Washakie Basins. They also indicated the formation has a thickness of 0 to 1,275 ft.

Darton and Siebenthal (1909) first described the rocks of the Rock River Formation of the Mesaverde Group (**Plate U**) in the northern Laramie Basin, but the formation was named by Gill et al. (1970). It grades westerly into the Allen Ridge Formation and easterly into the Pierre Shale (Gill et al., 1970). Gill et al. (1970) described it as light-gray to light-brown, very fine-to fine-grained sandstone that is locally shaly, with a few beds of soft sandy shale. They noted that this shallow-water marine unit has a maximum thickness of about 1,565 ft.

The Haystack Mountains Formation is the oldest unit of the Mesaverde Group and has a gradational contact with the underlying Steele Shale (**Plates S, U**). Gill et al. (1970) named three sandstone members of the unit: Hatfield (in upper part), O'Brien Spring (in middle part), and Tapers Ranch (at base) Sandstone Members. They described the unit as pale yellowish-gray, very fine- to fine-grained sandstone interbedded with gray to brownish-gray shale and sandy shale containing fossiliferous concretions of ironstone, limestone, or argillaceous sandstone. The sandstone is a near-shore to off-shore marine deposit, whereas the shales are deep marine deposits. Gill et al. (1970) reported a thickness of 850 to 2,550 ft.

In the Granite Mountains Uplift, Shirley Basin, and the Rawlins Uplift, the Mesaverde aquifer is confined from above by the Lewis confining unit and confined from below by either the Cody or Steele confining units (**Plates J, S**). The Mesaverde aquifer is overlain by the Wind River aquifer and confined from below by the Steele confining unit in the Hartville Uplift and Laramie Mountains (**Plate K**). The Mesaverde aquifer is overlain by the Lewis confining unit and confined from below by the Steele confining unit in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

The Mesaverde Group or Formation is defined as an aquifer by all previous investigators,

even though hydrogeologic characteristics of the individual formations (when elevated to group rank) composing the unit can vary. Collentine et al. (1981) defined the formation as a "major aquifer" in the Great Divide and Washakie Basins (**Plate S**), and Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plates J, U**). Collentine et al. (1981) summarized hydraulic properties for the Mesaverde aquifer throughout the Great Divide and Washakie Basins. The USGS defined the Mesaverde aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the formation as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Mesaverde aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Excluding oil and gas production, few wells are installed in the Mesaverde aquifer. Sandstone beds within the aquifer have potential for development for stock, domestic, or limited public-supply use, although water quality determined during this study would preclude many uses without treatment. Domestic or stock wells generally are completed only in areas where the aquifer crops out. Development of the aquifer has been very limited because of the availability of shallower and better sources of groundwater, availability of surface water in areas where the aquifer crops out, and towns or cities are not located close to the aquifer (Richter, 1981a). Confined conditions predominate, but unconfined (water-table conditions) are likely in Mesaverde aquifer outcrop areas.

In the Rawlins Uplift area, Berry (1960) noted limited potential for development of the Mesaverde aquifer. He noted that much of the Mesaverde Formation was unsaturated in the area, although the formation was saturated downdip in some locations and that "the sandstone beds probably will yield water to wells along the western flank of the Rawlins Uplift" (Berry, 1960, p. 22). He also noted that the area in which wells could be located in the saturated zone of the formation in the Rawlins Uplift area was small because of the steep dip of the beds in the area.

Welder and McGreevy (1966) reported that the groundwater development possibilities of the Mesaverde aquifer in the Great Divide and Washakie Basins were largely unknown. They also noted that groundwater development possibilities in the Almond Formation of the Mesaverde Group "are largely unknown but probably fair" and noted that yields of 20 to 100 gal/min were possible (Welder and McGreevy, 1966, Sheet 3).

Richter (1981a) evaluated the hydrogeology of the Mesaverde aquifer in the Laramie, Shirley, and Hanna Basin areas. In parts of these areas, he reported that the Mesaverde Formation contained a good aquifer that was laterally continuous and semiconfined. The aquifer is elevated, dissected, and unsaturated in the northwestern part of the Laramie Basin, so development potential in this area was reported to be poor. In the Hanna and Shirley Basins, the Mesaverde aquifer is structurally depressed, laterally continuous, and semiconfined; development potential for the aquifer is considered "good" along the margins of these basins because of saturation and presence of numerous springs. Along the flanks of Elk Mountain, Richter (1981a) speculated that groundwater development potential in this area was "excellent" because of faulting and fracturing in the area. The investigator reported that intergranular and fracture permeabilities were "large" and that yields from wells commonly ranged from 1 to 33 gal/min. Faulted and fractured zones within the Mesaverde aquifer were much more productive than undeformed areas. The Pine Ridge Sandstone was reported to be the most productive unit within the Mesaverde aquifer; reported yields ranged from 1 to 50 gal/min, and springs discharged 1 to 5 gal/min.

Recharge to the Mesaverde aquifer is primarily by infiltration of precipitation and streamflow on outcrops (Whitcomb and Lowry, 1968; Richter, 1981a, b). Richter (1981b, p. 80) noted recharge occurs to the Mesaverde aquifer in outcrop areas in the Casper Arch area. Where buried, interformational flow also may contribute to aquifer recharge (Richter, 1981a).

Discharge from the Mesaverde aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Whitcomb and Lowry, 1968; Richter, 1981a, b). In the

northwestern part of the Laramie Basin, springs discharge from the Mesaverde aquifer and "generally drain elevated and highly dissected outcrops" (Richter, 1981a, p. 68). The primary anthropogenic source of discharge is oil and gas wells.

Collentine et al. (1981, p. 61) constructed a generalized potentiometric map for the Mesaverde aquifer, including the eastern margin of the Great Divide and Washakie Basins. The map shows that groundwater flow in the area generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Chemical characteristics

The chemical characteristics of the Mesaverde aquifer (composed of groundwater-quality samples from the undivided Mesaverde Formation and different formations or members of the Mesaverde Group or Formation) are described in this section the report. In addition, the chemical characteristics of produced-water samples from two members of the Mesaverde Formation [Teapot Sandstone (equivalent to Pine Ridge Sandstone) and Parkman Sandstone Members of the Mesaverde Formation] identified by petroleum producers are described.

Central Wyoming basins (south)

The chemical composition of groundwater in the Mesaverde aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 17 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram E**). TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (53 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram E**; supplementary data tables). TDS concentrations ranged from 181 to 5,200 mg/L, with a median of 974 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (67 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), strontium (17 percent; USEPA HAL of 4,000 µg/L), ammonia (17 percent; WDEQ Class I standard of 0.5 mg/L), and zinc (14 percent; HAL of 2,000 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (88 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (76 percent; SMCL of 250 mg/L), iron (71 percent; SMCL of 300 µg/L), manganese (43 percent; SMCL of 50 µg/L), fluoride (12 percent; SMCL of 2 mg/L), and pH (8 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (76 percent of samples analyzed for the constituent; WDEQ Class II standard of 200 mg/L), manganese (29 percent; WDEQ Class II standard of 200 µg/L), SAR (24 percent; WDEQ Class II standard of 8), TDS (18 percent; WDEQ Class II standard of 2,000 mg/L), iron (14 percent; WDEQ Class II standard of 5,000 µg/L), and zinc (14 percent; WDEQ Class II standard of 2,000 µg/L). Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: pH (8 percent below lower WDEQ Class III limit of 6.5), TDS (6 percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (6 percent; WDEQ Class III standard of 3,000 mg/L).

The chemical composition of groundwater in the Mesaverde aquifer in the CBS also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed

in **Appendix F2**. TDS concentrations were variable and indicated that most waters were slightly saline (78 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,090 to 11,200 mg/L, with a median of 1,710 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (67 percent), chloride (33 percent; SMCL of 250 mg/L), sulfate (25 percent), and pH (22 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (44 percent; WDEQ Class II standard of 100 mg/L), iron (33 percent), sulfate (25 percent), and TDS (44 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: pH (22 percent above upper WDEQ Class III limit of 8.5), TDS (22 percent), and chloride (11 percent; WDEQ Class III limit of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 11 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Mesaverde aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from two wells (one sample was analyzed for major ions, and the other sample was analyzed for other constituents). Individual constituent concentrations for this sample are listed in **Appendix E6**. One TDS concentration (1,790 mg/L) indicated that waters were slightly saline (**Appendix E6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for the constituent exceeded proposed MCL, but did not exceed alternative MCL). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use in one sample: TDS, fluoride, and sulfate.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards in one sample were SAR, boron (WDEQ Class II standard of 750 µg/L), and sulfate. No characteristics or constituents exceeded State of Wyoming livestock standards

The chemical composition of groundwater in the Mesaverde aquifer in the CBN also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were moderately saline (67 percent of samples), and remaining waters were slightly saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 2,880 to 4,190 mg/L, with a median of 3,210 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality

standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), sulfate (100 percent), chloride (67 percent), and pH (33 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards in all three samples were TDS, chloride, and sulfate. Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

Great Plains

The chemical composition of groundwater in the Mesaverde aquifer in the GP was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for these samples are listed in **Appendix F6**. The TDS concentrations (5,010 and 15,400 mg/L) indicated that waters were moderately to very saline (**Appendix F6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards: TDS and chloride in both samples, and sulfate in one sample. Concentrations of one characteristic and one constituent was measured at greater than State of Wyoming livestock-use standards: TDS (in both samples), and chloride (in one sample). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in one of the produced-water samples.

7.3.6.1 Teapot Sandstone Member of Mesaverde Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Teapot Sandstone Member of Mesaverde Formation in the CBN was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations indicated that waters were moderately saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,240 to 1,730 mg/L, with a median of 1,420 mg/L.

Concentrations of some characteristics and constituents in water from the Teapot Sandstone Member of Mesaverde Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent) and sulfate (33 percent).

For agricultural and livestock use, concentrations of some characteristics and

constituents exceeded State of Wyoming standards in the CBN. Two constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (67 percent) and chloride (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Teapot Sandstone Member of Mesaverde Formation in the GP was characterized and the quality evaluated on the basis of 17 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram B**). TDS concentrations were variable and indicated that most waters were very saline (88 percent of samples), and remaining waters ranged from slightly to moderately saline (**Appendix F6**; **Appendix H4**, **diagram B**; supplementary data tables). TDS concentrations ranged from 2,880 to 17,200 mg/L, with a median of 14,400 mg/L.

Concentrations of some characteristics and constituents in water from the Teapot Sandstone Member of Mesaverde Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (100 percent), sulfate (8 percent), and iron (one sample analyzed for this constituent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent), chloride (100 percent), and sulfate (15 percent). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (94 percent) and chloride (94 percent). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 88 percent of produced-water samples.

7.3.6.2 Parkman Sandstone Member of Mesaverde Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Parkman Sandstone Member of the Mesaverde Formation in the CBN was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples), and remaining waters were moderately saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,370 to 4,780 mg/L, with a median of 1,660 mg/L.

Concentrations of some characteristics and constituents in water from the Parkman Sandstone Member of Mesaverde Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), pH (33 percent above upper limit), chloride (25 percent), and sulfate (25 percent).

For agricultural and livestock use, concentrations of some characteristics and

constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (25 percent), chloride (25 percent), and sulfate (25 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

Great Plains

The chemical composition of groundwater in the Parkman Sandstone Member of Mesaverde Formation in the GP was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**. TDS concentrations were variable and indicated that waters ranged from moderately saline to very saline (**Appendix F6**; supplementary data tables). TDS concentrations ranged from 3,140 to 17,400 mg/L, with a median of 11,000 mg/L.

Concentrations of some characteristics and constituents in water from the Parkman Sandstone Member of Mesaverde Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (100 percent), iron (in the one sample analyzed for this constituent), and pH (50 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent), chloride (100 percent), iron (in the one sample analyzed for this constituent), and sulfate (33 percent). Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: TDS (75 percent), chloride (75 percent), and pH (50 percent above upper limit). State of Wyoming Class IV TDS standards were exceeded in 50 percent of produced-water samples.

7.3.7 Cody confining unit

The physical and chemical characteristics of the Cody confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Cody confining unit consists of the Late Cretaceous Cody Shale (**Plates J, S**). The Cody Shale is equivalent to the Steele Shale and Niobrara Formation (**Plates J, S**) and is present in areas where the Niobrara Formation is poorly developed or missing (**Plates 1, 2**) (Weitz and Love, 1952; Reynolds, 1966; Gill et al., 1970). The Cody Shale is described as gray soft shale with thin gray sandstone and siltstone beds (Weitz and Love, 1952; Weimer and Guyton, 1961; Welder and McGreevy, 1966). Weitz and Love (1952) noted a smoky-gray limy shale at the base of the unit. There is a minor amount of bentonite in the unit (Weimer and Guyton, 1961; Welder and McGreevy, 1966). Weimer and Guyton (1961) indicated that this marine shale is as much as 4,500-ft thick. Parts of the Cody Shale are very important oil and gas reservoirs.

Because shale is the predominant lithology in the regionally extensive Cody Shale, and shale generally yields small quantities of water, the formation is considered to be a thick regional confining unit between the overlying Mesaverde aquifer and the underlying Frontier aquifer where present in the PtRB (**Plates J, S**) (Berry, 1960; Welder and McGreevy, 1966; Collentine et al., 1981; Richter, 1981a). The USGS defined the formation as a "confining unit" (Whitehead, 1996). These previous investigators also noted

that some sandstone lenses are locally present in the formation and will yield small quantities of water to wells, although the water likely would be highly mineralized. Hydrogeologic data describing the Cody confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical characteristics of the Cody confining unit (composed of groundwater-quality samples from the undivided Cody Shale and different members of the Cody Shale) are described in this section the report. In addition, the chemical characteristics of produced-water samples from one member of the Cody Shale (Shannon Sandstone Member of the Cody Shale) identified by petroleum producers are described.

Central Wyoming basins (south)

The chemical composition of groundwater in the Cody confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (5,110 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; USEPA SMCL of 500 mg/L and WDEQ Class III standard of 5,000 mg/L) and one constituent (sulfate; SMCL of 250 mg/L and WDEQ Class III standard of 3,000 mg/L) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (SAR and TDS; WDEQ Class II standards of 8 and 2,000 mg/L, respectively) and one constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards.

The chemical composition of groundwater in the Cody confining unit in the CBS also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (1,550 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS exceeded aesthetic standards for domestic use. Chloride exceeded State of Wyoming agricultural standards (WDEQ Class II standard of 100 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Cody confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (7,760 mg/L) indicated that the water was moderately saline (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Cody confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use, but concentrations of

two constituents exceeded health-based standards: arsenic and selenium (USEPA MCLs of 10 and 50 µg/L, respectively). One characteristic (TDS) and two constituents (selenium, which has a WDEQ Class III standard of 50 µg/L, and sulfate) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (SAR and TDS) and four constituents (boron, which has a WDEQ Class II standard of 750 µg/L, chloride, selenium, which has a WDEQ Class II standard of 20 µg/L, and sulfate) exceeded the State of Wyoming agricultural-use standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Cody confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 34 wells. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram D**). TDS concentrations were variable and indicated that most waters were moderately saline (38 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to briny (TDC concentrations greater than 34,999 mg/L) (**Appendix E6**; **Appendix G4**, **diagram D**; supplementary data tables). TDS concentrations ranged from 422 to 98,500 mg/L, with a median of 3,630 mg/L.

Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: strontium (in the one sample analyzed for this constituent, USEPA HAL of 4,000 µg/L), selenium (70 percent), nitrate plus nitrite (57 percent; MCL of 10 mg/L), molybdenum (10 percent; HAL of 40 µg/L), fluoride (8 percent; MCL of 4 mg/L), and cadmium 5 percent; MCL of 5 µg/L). Cadmium is not included in **Appendix E6** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: manganese (in the one sample analyzed for this constituent; SMCL of 50 µg/L), TDS (94 percent), sulfate (94 percent), fluoride (25 percent; SMCL of 2 mg/L), and chloride (16 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were lithium (in the one sample analyzed for this constituent; WDEQ Class II standard of 2,500 µg/L), sulfate (94 percent), TDS (74 percent), selenium (73 percent), SAR (44 percent), chloride (44 percent), boron (39 percent), and cadmium (5 percent; WDEQ Class II standard of 5 µg/L; supplementary data tables). Cadmium is not included in **Appendix E6** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: selenium (70 percent), sulfate (38 percent), TDS (32 percent), and nitrate plus nitrite (19 percent; WDEQ Class III standard of 100 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 19 percent of environmental water samples.

7.3.7.1 Shannon Sandstone Member of the Cody Shale

Central Wyoming basins (south)

The chemical composition of groundwater in the Shannon Sandstone Member of the Cody Shale in the CBS was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (7,570 and 17,500 mg/L) indicated that waters ranged from moderately saline ((TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Shannon Sandstone Member of the Cody Shale in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use and State of Wyoming agricultural- and livestock-use standards: TDS and chloride in both samples. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Shannon Sandstone Member of the Cody Shale in the CBN was characterized and the quality evaluated on the basis of 25 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram A**). TDS concentrations were variable and indicated that most waters were very saline (64 percent of samples), and remaining waters ranged from slightly saline to briny (**Appendix F5**; **Appendix H3**, **diagram A;** supplementary data tables). TDS concentrations ranged from 1,280 to 48,000 mg/L, with a median of 15,700 mg/L.

Concentrations of some characteristics and constituents in water from the Shannon Sandstone Member of the Cody Shale in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), sulfate (25 percent), and pH (7 percent below lower SMCL limit of 6.5 and 7 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent of samples analyzed for the constituent), TDS (96 percent), and sulfate (33 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (92 percent), chloride (88 percent; WDEQ Class III standard of 2,000 mg/L), and pH (7 percent below lower WDEQ Class III limit of 6.5 and 7 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 72 percent of produced-water samples.

7.3.8 Steele confining unit

The physical and chemical characteristics of the Steele confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Steele confining unit consists of the Late Cretaceous Steele Shale (**Plates J, K, S, T, U**) and is present throughout much of the PtRB, except in some areas where it cannot be differentiated from the underlying Niobrara Formation and both units are referred to as the Cody Shale. The Steele Shale has gradational contacts with the overlying Mesaverde Formation as well as with the underlying Niobrara Formation (**Plates J, K, S, T, U**). It is a dark-gray shale with some layers of limestone, sandstone, siltstone, and bentonite (Dobbin, Bowen, and Hoots, 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972; Gill et al., 1970; Naftz and Barclay, 1991). Sandstone is more common in the upper part

of the formation. The formation was deposited in a marine environment. The thickness varies from 2,300 to 5,000 ft, depending on how the upper and lower gradational contacts are chosen (Gill et al., 1970).

Because shale is the predominant lithology in the Steele Shale, and shale generally yields small quantities of water, the formation generally is considered to be a regional confining unit (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) or a regional leaky confining unit (Richter, 1981a). These previous investigators also noted that some sandstone lenses are present in the confining unit and will locally yield small quantities of water to wells, although water likely would be highly mineralized. Within the Steele Shale, Richter (1981a, p. 73) considered the Shannon Sandstone Member to be a "reliable, but undeveloped, source of groundwater." The investigator reported that water in the unit was under confined conditions, and artesian flows ranged from 1 to 25 gal/min at selected petroleum wells. Hydrogeologic data describing the Steele confining unit, including well-yield and other hydraulic properties, are summarized on **Plate 3.**

Central Wyoming basins (south)

The chemical composition of groundwater in the Steele confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as eight wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (43 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 175 to 17,900 mg/L, with a median of 3,420 mg/L.

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (75 percent; WDEQ Class I of 0.5 mg/L), strontium (67 percent; USEPA HAL of 4,000 µg/L), antimony (33 percent; USEPA MCL of 6 µg/L), arsenic (33 percent; MCL of 10 µg/L), molybdenum (33 percent; HAL of 40 µg/L), nickel (33 percent; HAL of 100µg/L), radon (33 percent of samples analyzed for the constituent exceeded proposed MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), selenium (33 percent; MCL of 50 µg/L), uranium (33 percent; MCL of 30 µg/L) nitrate plus nitrite (25 percent; MCL of 10 mg/L), and nitrate (12 percent; MCL of 10 µg/L). Nickel and selenium are not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (71 percent; SMCL of 500 mg/L), sulfate (71 percent; SMCL of 250 mg/L), manganese (67 percent; SMCL of 50 µg/L), iron (33 percent; SMCL of 300 µg/L), and chloride (29 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (71 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), manganese (67 percent; WDEQ Class II standard of 200 µg/L), SAR (57 percent; WDEQ Class II standard of 8), TDS (57 percent; WDEQ Class II standard of 2,000), cobalt (33 percent; WDEQ Class II standard of 50 µg/L), lithium (33 percent; WDEQ Class II standard of 2,500 µg/L), nickel (33 percent; WDEQ Class II standard of 200 µg/L; supplementary data tables), boron (29 percent; WDEQ Class II standard of 750 µg/L), chloride (29 percent; WDEQ Class II standard of 100 mg/L), and selenium (33 percent; WDEQ Class II standard of 20 µg/L). Nickel and selenium are not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: selenium (33 percent; WDEQ Class III standard of 50 µg/L), TDS (29

percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (29 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 14 percent of environmental water samples.

The chemical composition of groundwater in the Steele confining unit in the CBS also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (1,910 and 11,800 mg/L) indicated that waters ranged from moderately to very saline (**Appendix F2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and two constituents exceeded aesthetic standards for domestic use: TDS in both samples and chloride and sulfate in one sample. TDS, chloride and sulfate exceeded State of Wyoming agricultural-use standards in one sample. TDS and chloride (WDEQ Class III standard of 2,000 mg/L) exceeded State of Wyoming livestock-use standards in one sample. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Steele confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Individual constituent concentrations for this sample are listed in **Appendix E6**. TDS concentrations were variable and indicated that waters ranged from fresh to moderately saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 511 to 3,160 mg/L, with a median of 1,530 mg/L.

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent) and sulfate (67 percent).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent), sulfate (67 percent), boron (33 percent), and TDS (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.9 Niobrara confining unit

The physical and chemical characteristics of the Niobrara confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Niobrara confining unit consists of the Late Cretaceous Niobrara Formation (**Plates J, K, M, S, T, U**) and generally is deeply buried throughout most areas of the PtRB. In some areas, the Niobrara Formation cannot be differentiated from the overlying Steele Shale and both units are referred to as the Cody Shale (Love et al., 1993). The Niobrara Formation is a dark-gray calcareous shale with some light-colored layers of limestone, chalk, and sandstone (Dobbin, Bowen, and Hoots, 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972). There are some thin layers of white crystalline calcite (Dobbin, Bowen, and Hoots, 1929). Hale (1961) noted that the Niobrara Formation is lighter in color and more calcareous than the overlying Steele Shale. The formation was deposited in a marine environment. Reported thickness in the PtRB ranges from 0 to

1,475 ft (Dobbin, Bowen, and Hoots, 1929; Rapp et al., 1957; Berry, 1960; Morris and Babcock, 1960; Lowry and Crist, 1967; Harshman, 1968, 1972; Richter, 1981a).

Similar to the previously described Lewis, Cody, and Steele Shales, shale is the predominant lithology in the Niobrara Formation and the formation generally is considered to be a regional leaky confining unit or confining unit (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Libra et al., 1981; HydroGeo, Inc., 2003) (**Plates J, K, M, S, T, U**). The USGS defined the formation as a "confining unit" (Whitehead, 1996). These previous investigators also noted that sandstone lenses are present in the formation and will yield small quantities of water to wells, although water is likely highly mineralized. Hydrogeologic information describing the Niobrara confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate 3**.

Sweetwater Arch

The chemical composition of groundwater in the Niobrara confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (8,580 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards (TDS: USEPA SMCL of 500 mg/L, WDEQ Class II standard of 2,000 mg/L, and WDEQ Class III standard of 5,000 mg/L; chloride: SMCL of 250 mg/L, WDEQ Class II standard of 100 mg/L, and WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Niobrara confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 679 to 2,950 mg/L, with a median of 1,510 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), ammonia (50 percent; WDEQ Class I of 0.5 mg/L), and nitrate (20 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent) and sulfate (50 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were boron (67 percent of samples analyzed for the constituent; WDEQ Class II standard 750 µg/L), SAR (50 percent; WDEQ

Class II standard of 8), TDS (50 percent), chloride (50 percent), and sulfate (50 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Niobrara confining unit in the CBS also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (44 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 4,360 to 57,500 mg/L, with a median of 29,000 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (50 percent; SMCL of 300 µg/L), sulfate (43 percent), and pH (22 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), sulfate (57 percent), iron (50 percent; WDEQ Class II standard of 5,000 µg/L), and pH (11 percent above upper WDEQ Class II limit of 9.0). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (78 percent), chloride (78 percent), and pH (22 percent above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 67 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Niobrara confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (6,120 and 10,300 mg/L) indicated that waters ranged from moderately to very saline (**Appendix F5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards: TDS and chloride in both samples. Sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards in one sample. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Great Plains

The chemical composition of groundwater in

the Niobrara confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of 42 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram C**). TDS concentrations were variable and indicated that most waters were very saline (40 percent of samples) or briny (TDS concentrations greater than 34,999 mg/L) (40 percent of samples), and remaining waters were moderately saline (**Appendix F6**; **Appendix H4**, **diagram C;** supplementary data tables). TDS concentrations ranged from 3,550 to 112,000 mg/L, with a median of 27,200 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (100 percent), pH (5 percent below lower SMCL limit of 6.5 and 2 percent above upper SMCL limit of 8.5), and sulfate (4 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (60 percent), and sulfate (7 percent). Characteristics and constituents in produced-water samples measured at concentrations at greater than State of Wyoming livestock-use standards were TDS (90 percent), chloride (90 percent), and pH (5 percent below lower WDEQ Class III limit of 6.5 and 2 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 81 percent of produced-water samples.

7.3.10 Frontier aquifer

The physical and chemical characteristics of the Frontier aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Frontier aquifer consists of the Late Cretaceous Frontier Formation (**Plates J, K, S, T, U**), which is present throughout most of the PtRB with the exception of the Granite Mountains area, with outcrops occurring near the uplifts (**Plates 1, 2**). The Frontier Formation is predominately a dark-gray shale with beds of sandstone near the top (Wall Creek Sandstone Member). In the Shirley Basin, Harshman (1968, 1972) described the lower part of the formation as dark-gray carbonaceous shale and the upper part as similar shale with interbedded gray to brownish-gray fine- to medium-grained sandstone. Harshman (1968, 1972) described the upper part of the Wall Creek Sandstone as a series of fine-to coarse-grained buff to greenish-gray sandstone beds that are interbedded with dark-gray shale. He also noted that the basal part can be a reddish to purplish-gray siltstone or sandy siltstone in some areas, whereas other areas have a basal part that is a gray, silty sandstone and shale. In the Hanna and Carbon Basins, the Frontier Formation is described as a dark-gray to black shale, and the Wall Creek Sandstone Member is described as sandstone interbedded with some shale (Dobbin, Bowen, and Hoots, 1929). In the western part of Carbon County, the Frontier Formation is described as gray to grayish-brown calcareous silty to sandy shale that has lenses of bentonite and beds of fine- to medium-grained sandstone (Berry, 1960; Merewether and Cobban, 1972). Merewether and Cobban (1972) referred to the lower part as the Belle Fourche Shale Member and the upper part as the Wall Creek Sandstone Member. They described

an unnamed middle member as brownish-gray carbonaceous siltstone and shale or silty very fine- to fine-grained sandstone. In the adjacent Wind River Basin (WRB) and Wind River Mountains, this unnamed middle member has been named the Emigrant Gap Member (Johnson et al., 2007, and references therein).

The Frontier Formation is a marine deposit that accumulated on shallow shelves as channel deposits and near-shore and offshore bars (Merewether et al., 1979). The Frontier Formation ranges from 500- to 1,230-ft thick (Merewether and Cobban, 1972). The Wall Creek Sandstone Member ranges from 40 to 350 ft in thickness (Dobbin, Hoots, et al., 1929; Merewether and Cobban, 1972).

The Frontier Formation is defined as an aquifer by previous investigators. Development of the aquifer has been very limited because of the availability of shallower and better sources of groundwater and availability of surface water in areas where the formation crops out (Richter, 1981a). Sandstone beds within the aquifer, primarily in the Wall Creek Sandstone Member, are used primarily to supply water for stock purposes, but occasionally are used to supply water for domestic purposes (Berry, 1960; Whitcomb and Lowry, 1968; Collentine et al., 1981; Richter, 1981a, b). In the Rawlins Uplift area, Berry (1960, p. 20) noted that sandstone beds in the Frontier Formation "yield moderate amounts of water." He noted that water in the Frontier aquifer generally is under confined conditions (artesian pressure) and that wells completed in the aquifer will flow at some locations. Collentine et al. (1981) defined the formation as a "secondary aquifer" confined above by shale of the Cody or Niobrara confining units and below by the Mowry confining unit in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. He (Richter, 1981a, p. 70) reported that little hydraulic information was available describing the Frontier aquifer in the general vicinity of the Laramie, Shirley, and Hanna Basins, but development potential for groundwater supplies was "good" because of good primary permeability and saturation in upper sandstones, as well as "extensive" areas of potential recharge where the aquifer crops out along the Laramie, Shirley, and Freezeout Mountains. In the adjacent WRB, Richter (1981b, Table IV-1, p. 49) defined only the upper two-thirds of the Frontier Formation as a regional aquifer, and the lower one-third was defined as a confining unit. The Frontier aquifer is confined from above by the Cody or Niobrara confining units and confined from below by the Mowry-Thermopolis confining unit (**Plates J, K, S, T, U**). Hydrogeologic data describing the Frontier aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Water in the Frontier aquifer generally is under semiconfined or confined conditions, depending on confining layer continuity (Whitcomb and Lowry, 1968; Richter, 1981a, b). Richter (1981a, p. 70) noted that "semiconfined systems exist in the southern and central parts of the Laramie Basin where confining shales are elevated and dissected" and that "groundwater is confined in the northwestern part of the Laramie Basin because the unit is buried and confining units are continuous." In the WRB adjacent to the PtRB, alternating layers of sandstone and shale creates a series of confined sandstone subaquifers within the Frontier aquifer (Richter, 1981b, p. 76); it is likely this hydrogeologic interpretation of the Frontier aquifer is applicable to the unit throughout the PtRB.

Collentine et al. (1981) summarized hydraulic properties for the Frontier aquifer in the Great Divide and Washakie Basins. The area of the aquifer within Carbon County, on the eastern margin of the Great Divide and Washakie Basins, was considered the most "productive." Variability in transmissivity estimated from aquifer and drill-stem tests was attributed to varying percentages of bentonite and shale within tested open intervals. In addition, the investigators constructed a generalized potentiometric map for the Frontier aquifer within the basins, including Carbon County (Collentine et al., 1981, Figure V-4, p. 63). The map shows that groundwater flow in the area generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Chemical characteristics

The chemical characteristics of the Frontier aquifer are described in this section the report. In

addition, the chemical characteristics of produced-water samples from one member of the Frontier Formation (Wall Creek Sandstone Member) identified by petroleum producers are described. Groundwater quality of the Frontier aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Frontier aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 1,280 to 3,330 mg/L, with a median of 1,740 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and fluoride (33 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), SAR (33 percent; WDEQ Class II standard of 8), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), and boron (33 percent; WDEQ Class II standard of 750 µg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Frontier aquifer in the SA also was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 2,150 to 10,100 mg/L, with a median of 8,290 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (75 percent; SMCL of 250 mg/L), pH (50 percent above upper limit), iron (50 percent; SMCL of 300 µg/L), and sulfate (25 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the

constituent), chloride (100 percent; WDEQ Class II standard of 100 mg/L), iron (50 percent; WDEQ Class II standard of 5,000 µg/L), and sulfate (25 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (75 percent; WDEQ Class III standard of 5,000 mg/L), chloride (75 percent; WDEQ Class III standard of 2,000 mg/L), and pH (50 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 25 percent of produced-water samples.

Central Wyoming basins (south)

The chemical composition of groundwater in the Frontier aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (358 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for most uses. One characteristic (SAR) exceeded State of Wyoming agricultural-use standards.

The chemical composition of groundwater in the Frontier aquifer in the CBS also was characterized and the quality evaluated on the basis of 26 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram A**). TDS concentrations were variable and indicated that most waters were very saline (62 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations great than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram A**; supplementary data tables). TDS concentrations ranged from 3,210 to 47,600 mg/L, with a median of 12,200 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (50 percent), pH (25 percent above upper SMCL limit of 8.5 and 4 percent below lower SMCL limit of 6.5), and sulfate (13 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), and sulfate (17 percent). Characteristics and constituents in produced-water samples measured at concentrations greater than State of Wyoming livestock-use standards were TDS (96 percent), chloride (96 percent), and pH (25 percent above upper WDEQ Class III limit of 8.5 and 4 percent below lower WDEQ Class III limit of 6.5). The State of Wyoming Class IV standard for TDS was exceeded in 69 percent of produced-water samples.

Sierra Madre

The chemical composition of groundwater in the Frontier aquifer in the Sierra Madre (SM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (714 mg/L) indicated that the water was fresh (**Appendix E3**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. Two characteristics (pH above upper limit and TDS) exceeded aesthetic standards for domestic use. Two characteristics (pH above upper WDEQ Class II limit of 9 and SAR) exceeded the State of Wyoming agricultural-use standards. One characteristic (pH above upper limit) exceeded State of Wyoming livestock-use standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Frontier aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (192 mg/L) indicated the water was fresh. On the basis of the few characteristics and constituents analyzed for, the quality of water from Frontier aquifer in the MBM was likely suitable for most uses. No characteristics or constituents in the Frontier aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental water sample.

Laramie Mountains

The chemical composition of groundwater in the Frontier aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E5**. TDS concentrations were highly variable and indicated that most waters were very saline (33 percent of samples), and remaining waters ranged from fresh to briny (**Appendix E5**; supplementary data tables). TDS concentrations ranged from 646 to 37,800 mg/L, with a median of 10,800 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: lead (100 percent; MCL (action level) of 15 µg/L; supplementary data tables), nitrate plus nitrite (in the one sample analyzed for this constituent; MCL of 10 mg/L), selenium (75 percent; MCL of 50 µg/L), strontium (50 percent; HAL of 4,000 µg/L), and fluoride (40 percent; MCL of 4 mg/L). Lead is not included in **Appendix E5** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), fluoride (40 percent), and chloride (17 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were selenium (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 20 µg/L), sulfate (100 percent), TDS (80 percent), boron (80 percent), SAR (50 percent), chloride (50 percent), and copper (50 percent; WDEQ Class II standard of 200 µg/L; supplementary data tables). Copper is not included in **Appendix E5** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents in environmental water samples measured at greater than State of Wyoming livestock-use standards were selenium (75 percent; WDEQ Class III standard of 50 µg/L), TDS (60 percent), and sulfate (50 percent; WDEQ Class III standard of 3,000 mg/L). The State of Wyoming Class IV standard for TDS was exceeded in 60 percent of environmental water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Frontier aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality

evaluated on the basis of environmental water samples from as many as nine wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (56 percent of samples), and remaining waters ranged from fresh to moderately saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 708 to 3,570 mg/L, with a median of 1,470 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: fluoride (67 percent of samples analyzed for the constituent) and nitrate plus nitrite (33 percent). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (78 percent), fluoride (67 percent), and pH (22 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent of samples analyzed for the constituent), boron (100 percent), sulfate (89 percent), pH (22 percent above upper limit), TDS (22 percent), and chloride (22 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (22 percent above upper limit).

The chemical composition of groundwater in the Frontier aquifer in the CBN also was characterized and the quality evaluated on the basis of 22 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram B**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples), and remaining waters ranged from slightly to very saline (**Appendix F5**; **Appendix H3**, **diagram B;** supplementary data tables). TDS concentrations ranged from 2,260 to 34,100 mg/L, with a median of 6,850 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (91 percent), sulfate (45 percent), and pH (14 percent above upper limit and 5 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (95 percent), sulfate (55 percent), and pH (5 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (68 percent), chloride (55 percent), pH (14 percent above upper limit and 5 percent below lower limit), and sulfate (5 percent). State of Wyoming Class IV standard for TDS was exceeded in 36 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Frontier aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram D**). TDS concentrations were variable and indicated that most waters were

briny (TDS concentrations greater than 34,999 mg/L) (64 percent of samples), and remaining waters ranged from fresh to very saline (**Appendix F6**; **Appendix H4**, **diagram D;** supplementary data tables). TDS concentrations ranged from 691 to 91,600 mg/L, with a median of 41,200 mg/L.

Concentrations of some characteristics and constituents in produced-water from the Frontier aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (100 percent), chloride (91 percent), and pH (45 percent below lower limit and 9 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent of samples analyzed for the constituent), iron (100 percent), TDS (91 percent), and pH (9 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (82 percent), chloride (82 percent), and pH (45 percent below lower limit and 9 percent above upper limit).The State of Wyoming Class IV standard for TDS was exceeded in 82 percent of produced-water samples.

7.3.10.1 Wall Creek Sandstone Member of Frontier Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Wall Creek Sandstone Member of Frontier Formation in the CBN also was characterized and the quality evaluated on the basis of 40 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram C**). TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from slightly to very saline (**Appendix F5**; **Appendix H3**, **diagram C;** supplementary data tables). TDS concentrations ranged from 2,300 to 18,300 mg/L, with a median of 3,010 mg/L.

Concentrations of some characteristics and constituents in water from the Wall Creek Sandstone Member of Frontier Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (42 percent), chloride (92 percent), and pH (14 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (98 percent), and sulfate (46 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were: TDS (20 percent), chloride (18 percent), and pH (14 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 2 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Wall Creek Sandstone Member of the Frontier Formation in the GP also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for these samples are listed in **Appendix F6**. The TDS concentrations (3,340 and 3,410 mg/L) indicated that the water was moderately saline.

Concentrations of some characteristics and constituents in produced-water from the Wall Creek Sandstone Member of Frontier Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS (both samples), chloride (both samples), and pH (one sample) exceeded aesthetic standards for domestic use. TDS and chloride exceeded agricultural-use standards in both samples. In one sample, pH (above upper limit) exceeded State of Wyoming livestock standards.

7.3.11 Carlile, Greenhorn, and Belle Fourche confining units

The physical and chemical characteristics of the Carlile, Greenhorn, and Belle Fourche confining units in the PtRB are described in this section of the report.

Physical characteristics

The Carlile, Greenhorn, and Belle Fourche confining units consist of the Late Cretaceous Carlile Shale, Greenhorn Formation, and Belle Fourche Shale, respectively (**Plate M**). All three confining units are composed primarily of shale with some limestone and sandstone (Love et al., 1993), and are deeply buried in the Denver-Julesburg Basin. The formations were deposited in a marine environment. Combined thickness of the three confining units in the Denver-Julesburg Basin is as much as 1,400 ft or more [these rocks were identified as the Frontier Formation consisting of "formations from top of Lower Cretaceous to base of Niobrara Formation" in Libra et al. (1981, Table IV-1, p. 40)].

Like the other Upper Cretaceous confining units composed primarily of shale deposited in a marine environment (Lewis, Cody, and Steele Shales, and the Niobrara Formation), shale is the predominant lithology in the Carlile Shale, Greenhorn Formation, and Belle Fourche Shale; consequently, all three lithostratigraphic units are defined as confining units (Libra et al., 1981) (**Plate M**). Libra et al. (1981, Table IV-1, p. 40) also noted that "dispersed sandstones might yield water."

Chemical characteristics

The chemical composition of groundwater in the Greenhorn confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (2,010 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L).

Concentrations of some characteristics and constituents in water from the Greenhorn confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 8.5, and 250 mg/L, respectively). TDS, chloride, and sulfate exceeded agricultural-use standards (WDEQ Class II standards of 2,000 mg/L,

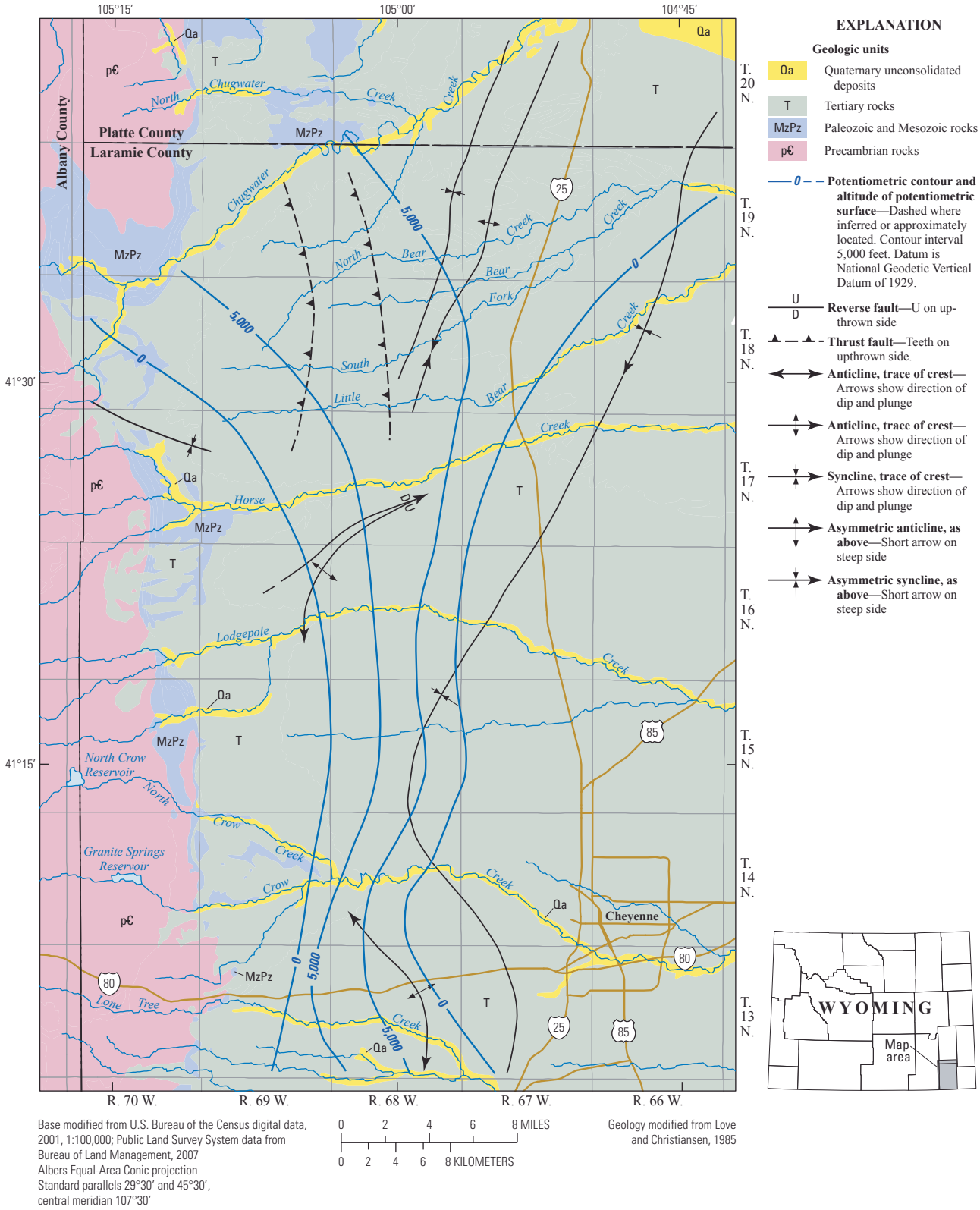


Figure 7-8. Generalized potentiometric-surface map for the Muddy Sandstone aquifer, Laramie County, Wyoming (modified from Wiersma, 1989).

100 mg/L, and 200 mg/L, respectively). One characteristic (pH above upper WDEQ Class III limit of 8.5) exceeded State of Wyoming livestock standards.

7.3.12 Mowry-Thermopolis confining unit and Muddy Sandstone aquifer

The physical and chemical characteristics of the Mowry-Thermopolis confining unit and Muddy Sandstone aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Mowry-Thermopolis confining unit is composed primarily of the Mowry and Thermopolis Shales, but also contains the Muddy Sandstone aquifer (**Plates J, K, M, S, T, U**). The Mowry and Thermopolis Shales and the Muddy Sandstone are present throughout the PtRB, with outcrops occurring near the uplifts (**Plates 1, 2**).

The Late Cretaceous Mowry Shale is a gray to deep-brown to black siliceous marine shale with beds of bentonite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Welder and McGreevy, 1966; Harshman, 1972). Harshman (1972) noted that some of the bentonite beds are 2- to 3-ft thick and some are associated with shale beds that contain considerable calcium carbonate. The Mowry Shale is a marine shale that contains numerous fish scales. It ranges in thickness from 80 to 525 ft (Welder and McGreevy, 1966; Lowry and Crist, 1967; Harshman, 1972; Libra et al., 1981; Richter, 1981a, and references therein).

The Early Cretaceous Thermopolis Shale is a gray to black shale with thin beds of sandstone, siltstone, and bentonite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Welder and McGreevy, 1966; Harshman, 1972). The Early Cretaceous Muddy Sandstone, sometimes referred to as the Muddy Sandstone Member of the Thermopolis Shale in earlier publications, is a buff to gray, silty, fine- to medium-grained sandstone (Berry, 1960; Harshman, 1972). In earlier studies in the Denver-Julesburg Basin, the Thermopolis Shale commonly was identified as the "Skull Creek Shale" and the Muddy Sandstone as the "Newcastle Sandstone." Harshman (1972) described four parts of the Thermopolis Shale: (1) a basal gray to black carbonaceous shale; (2) the Muddy Sandstone; (3) a brown to gray fine-grained sandstone interbedded with siltstone and shale that has a lignite bed at the top with associated thin, limy sandstone beds; and (4) an interval of sandy siltstone and shale at the top interbedded with siliceous shale that is typical of the Mowry Shale. The Thermopolis Shale primarily is of marine origin; an exception is the third unit of Harshman (1972), which is of paludal (marsh-like) origin. Curry (1962) indicated that the Muddy Sandstone is of shallow marine origin in some parts and terrestrial and fresh-water origin in other parts. The Thermopolis Shale ranges in thickness from 70 to 200 ft or more (Welder and McGreevy, 1966; Lowry and Crist, 1967; Harshman, 1972; Lowry et al., 1973; Libra et al., 1981; Richter, 1981a, and references therein). The Muddy Sandstone ranges in thickness from 70 to 110 ft or more (Lowry and Crist, 1967; Libra et al., 1981, and references therein; Richter, 1981a, and references therein).

Like the previously described Lewis, Cody, and Steele Shales, and Niobrara Formation, shale is the predominant lithology in the Mowry and Thermopolis Shales; consequently, both units are considered to be regional confining units or leaky confining units throughout the PtRB (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Collentine et al., 1981; Libra et al., 1981; Richter, 1981a, b) (**Plates J, K, M, S, T, U**). The USGS defined the formations as "confining units" (Whitehead, 1996). In all parts of the PtRB except the Denver-Julesburg Basin, the Mowry-Thermopolis confining unit separates the underlying Cloverly aquifer from the overlying Frontier aquifer (**Plates J, K, S, T, U**). In the Denver-Julesburg Basin, the Mowry-Thermopolis confining unit underlies the Belle Fourche confining unit and overlies the Inyan Kara aquifer (**Plate M**).

The Muddy Sandstone between the Mowry and Thermopolis Shales is defined as an aquifer by all investigators, although many note that groundwater quality may preclude some uses (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Collentine et al., 1981; Libra et al., 1981; Richter, 1981a, b) (**Plates J, K, M, S, T, U**). The Muddy Sandstone aquifer is a major oil and gas reservoir in the PtRB. Permeability in the

Muddy Sandstone aquifer is generally low because of tight cementation and silty matrix; however, permeability can be fracture enhanced in some areas of deformation (Richter, 1981b, p. 75).

As a part of a study evaluating structural obstruction of recharge to Paleozoic hydrogeologic units in the western Denver-Julesburg Basin along the eastern flank of the Laramie Mountains, Wiersma (1989, Plate 1) and Wiersma et al. (1989, Plate 1) constructed a potentiometric-surface map of the Muddy Sandstone aquifer. The map, reproduced herein as **Figure 7-8**, indicates that the general direction of groundwater flow is to the east from the Laramie Mountains.

With the exception of oil and gas wells, very few wells are installed in the Mowry and Thermopolis confining units and the Muddy Sandstone aquifer; development is limited to low-yield wells located along the structural basin margins where the formations crop out and drilling depths are relatively shallow. Most hydrogeologic information describing the Mowry and Thermopolis confining units and the Muddy Sandstone aquifer is from oil and gas well data. Hydrogeologic information including well-yield and spring-discharge measurements and other hydraulic properties for the Mowry-Thermopolis confining unit and associated Muddy Sandstone aquifer is summarized on **Plate 3.**

Chemical characteristics

Groundwater quality of the Muddy Sandstone aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Muddy Sandstone aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of six produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (50 percent of samples) or moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (50 percent) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,520 to 7,090 mg/L, with a median of 3,260 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), iron (100 percent; SMCL of 300 µg/L), chloride (83 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (100 percent of samples analyzed for the constituent; WDEQ Class II standard 5,000 µg/L), chloride (83 percent; WDEQ Class II standard of 100 mg/L), TDS (67 percent; WDEQ Class II standard of 2,000 mg/L), sulfate (33 percent; WDEQ Class II standard of 200 mg/L), and pH (17 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (50 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and

chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Muddy Sandstone aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of 40 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram B**). TDS concentrations were variable and indicated that most waters were moderately saline (62 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram B**; supplementary data tables). TDS concentrations ranged from 1,380 to 18,300 mg/L, with a median of 6,250 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (85 percent), sulfate (39 percent), and pH (19 percent above upper SMCL limit of 8.5 and 6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (98 percent of samples analyzed for the constituent), TDS (90 percent), and sulfate (39 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (55 percent), chloride (52 percent), pH (19 percent above upper WDEQ Class III limit of 8.5 and 6 percent below lower WDEQ Class III limit of 6.5), and sulfate (3 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 15 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Mowry confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (1,320 mg/L) indicated that the water was slightly saline (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mowry confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. Two constituents exceeded the State of Wyoming agricultural-use standards: boron (in the one sample analyzed for this constituent, the concentration was greater than the WDEQ Class II standard of 750 µg/L) and sulfate. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the LM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (76 mg/L) indicated that the water was fresh (TDS

concentration less than or equal to 999 mg/L) (**Appendix E5**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Muddy Sandstone aquifer in the LM was suitable for most uses. No characteristics or constituents in the Muddy Sandstone aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental sample.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the LM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F4**. The TDS concentration (2,680 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and sulfate exceeded aesthetic standards for domestic use. TDS and sulfate exceeded State of Wyoming agricultural-use standards. One characteristic (pH above upper limit) exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Muddy Sandstone aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 51 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram D**). TDS concentrations were variable and indicated that most waters were moderately saline (41 percent of samples) or very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (41 percent of samples), and remaining waters were slightly saline (**Appendix F5**; **Appendix H3**, **diagram D;** supplementary data tables). TDS concentrations ranged from 1,360 to 16,700 mg/L, with a median of 8,490 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (in the one sample analyzed for this constituent), chloride (90 percent), sulfate (24 percent), and pH (8 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the one sample analyzed for this constituent), chloride (96 percent), TDS (92 percent), and sulfate (26 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (69 percent), chloride (67 percent), and pH (8 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 41 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Muddy Sandstone aquifer in the Great

Plains (GP) also was characterized and the quality evaluated on the basis of 31 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram E**). TDS concentrations were variable and indicated that most waters were very saline (58 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F6**; **Appendix H4**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,240 to 50,300 mg/L, with a median of 11,000 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (90 percent), iron (in one of two samples analyzed for this constituent), sulfate (43 percent), and pH (10 percent above upper limit and 3 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (97 percent of samples analyzed for the constituent), chloride (94 percent), sulfate (48 percent), and pH (3 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (84 percent), chloride (84 percent), pH (10 percent above upper limit and 3 percent below lower limit), and sulfate (5 percent). The State of Wyoming Class IV standard for TDS was exceeded in 61 percent of produced-water samples.

7.3.13 Cloverly aquifer

The physical and chemical characteristics of the Cloverly aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Cloverly aquifer consists of the Early Cretaceous Cloverly Formation (**Plates J, K, S, T, U**), which is present throughout the basins of the PtRB, with outcrops occurring near the uplifts (**Plates 1, 2**). The Cloverly Formation has been divided into three parts: (1) an upper fine- to coarse-grained white to buff to gray quartzose sandstone, (2) a middle sequence of green shale to gray carbonaceous shale with interbedded buff, fine-grained, well-cemented, silty sandstone and some thin bentonite layers, and (3) a lower light-gray to white, fine-to medium-grained to conglomeratic sandstone with chert pebbles (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960; Harshman, 1972). The upper part of the formation is equivalent to the Dakota Sandstone, the middle part to the Fuson Shale, and the lower part to the Lakota Sandstone of adjacent areas (Agatston, 1951). Based on fossil assemblages, Curry (1962, p. 118) reported that terrestrial and fresh-water depositional environments probably persisted during the Early Cretaceous Epoch in central Wyoming. He also stated that considerable evidence exists that the uppermost fluvial deposits of the Cloverly Formation were partially reworked by the advancing Cretaceous seas (Curry, 1962, p. 118). The Cloverly Formation ranges from 50- to 200-ft in thickness in the Laramie, Shirley, and Hanna Basins (Harshman, 1972; Richter, 1981a, and references therein). In the area between Miller Hill and Rawlins, the average thickness of the Cloverly Formation has been estimated to be about 90 ft (Anderson and Kelly, Inc., 1984, p. 24).

The Cloverly Formation is defined as an aquifer by previous investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973;

Collentine et al., 1981; Richter, 1981a). Collentine et al. (1981) defined the formation as a "major aquifer" in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "major aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. The USGS also defined the formation as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Lower Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). The Cloverly aquifer is confined from above by the Mowry-Thermopolis confining unit (**Plates J, K, S, T, U**) and confined from below by the Morrison confining unit (**Plates J, S**) or Morrison aquifer and confining unit (**Plates K, T, U**). The Cloverly aquifer is used as a source of water for stock, domestic, and public-supply purposes. Stock and domestic wells generally are completed in the Cloverly aquifer only in areas where the Cloverly Formation crops out. Hydrogeologic data describing the Cloverly aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

In the Rawlins Uplift area, Berry (1960, p. 19) described the Cloverly Formation as an artesian aquifer with "sufficient pressure to flow at the land surface." He also reported that water from the Cloverly aquifer was the best quality for domestic and municipal use of all hydrogeologic units he examined in the Rawlins Uplift area.

In a study evaluating further development of the municipal water supply for the city of Rawlins, James M. Montgomery, Consulting Engineers, Inc. (1983b) conducted a new aquifer test of a well ("Rawlins-Cloverly well") previously examined by Berry (1960). They reported that the similarity in transmissivity estimates from different aquifer tests suggested "regional homogeneity" for the Cloverly aquifer in the area.

Collentine et al. (1981) described the hydrogeology of the Cloverly aquifer in the Great Divide and Washakie Basins. The area of the aquifer on the eastern margin of the Great Divide in the vicinity of the Rawlins Uplift was defined as a "major Mesozoic aquifer." The investigators noted that the Cloverly aquifer was deeply buried throughout most of the Great Divide and Washakie Basin areas. In addition, the investigators constructed a generalized potentiometric map for the Cloverly aquifer within the basins, including the western part of Carbon County (Collentine et al., 1981, Figure V-5, p. 65). The map shows that groundwater flow in the aquifer in Carbon County generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Richter (1981a) described the Cloverly aquifer in the Laramie, Shirley, and Hanna Basin areas. The investigator reported that the aquifer was confined throughout the area and had "good" intergranular porosity and permeability. Richter (1981a) also stated that there were two permeable zones within the Cloverly Formation—the Lakota and Dakota Sandstones separated by the Fuson Shale. He considered the Lakota and Dakota Sandstones as "subaquifers" within the Cloverly Formation, separated by the Fuson Shale, which he defined as a leaky confining unit allowing hydraulic connection through faults and fractures. He also noted that transmissivity was larger in "tectonically deformed areas." Richter (1981a) also stated that the Lakota Sandstone was the most productive zone within the Cloverly Formation.

Wells completed in the Lakota and Dakota subaquifers of the Cloverly aquifer provide the public-water supply for the town of Elk Mountain (Weston Engineering, Inc., 1995a, b). The Cloverly aquifer is the only source of drinking water for the town. Consequently, the Cloverly aquifer in the vicinity of the town received a "sole-source aquifer" designation by the USEPA in 1998 (U.S. Environmental Protection Agency, 2005). The EPA defines a sole aquifer as "an aquifer that supplies at least 50 percent of the drinking water consumed in the area overlying the aquifer. These areas may have no alternative drinking water source(s) that could physically, legally and economically supply all those who depend on the aquifer for drinking water. For convenience, all designated sole or principal source aquifers are referred to as "sole source aquifers" (SSAs)." The designation prohibits the use of federal funds for any project which could pollute the sole source aquifer. This is the only "sole-source aquifer" designation in the entire State of Wyoming.

In their study of the Cloverly aquifer in the vicinity of Miller Hill, Anderson and Kelly, Inc. (1984, p. 25) speculated that recharge to the Cloverly aquifer occurs in three ways:

direct infiltration of precipitation on outcrops; infiltration from perennial streamflow losses; and interformational movement. They noted that recharge from direct infiltration of precipitation on outcrops is likely "significant" because of Cloverly aquifer outcrop in the study area. The investigators (Anderson and Kelly, Inc., 1984, p. 25) hypothesized that the Cloverly aquifer may receive recharge from "extensive areas of subcrop beneath the Tertiary deposits in Miller Hill."

Chemical characteristics

Groundwater quality of the Cloverly aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Cloverly aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well and two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples) and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 241 to 2,680 mg/L, with a median of 484 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L and the alternative MCL of 4,000 pCi/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (33 percent; USEPA SMCL of 500 mg/L), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (33 percent of samples analyzed for the constituent; WDEQ Class II standard 8), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), and sulfate (33 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Cloverly aquifer in the SA also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were slightly saline (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,530 to 5,190 mg/L, with a median of 3,780 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (in the one sample analyzed for this constituent; SMCL of 300 µg/L), chloride (67 percent; SMCL of 250 mg/L), pH (33 percent above upper SMCL limit of 8.5), and sulfate (33 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the one sample analyzed for this constituent; WDEQ Class II standard of 5,000 µg/L), TDS (67 percent), chloride (67 percent; WDEQ Class II standard of 100 mg/L), and sulfate (33 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (33 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Cloverly aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as nine wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (78 percent of samples) and remaining waters ranged from slightly to moderately saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 188 to 4,480 mg/L, with a median of 282 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: fluoride (12 percent; USEPA MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (50 percent), TDS (33 percent), fluoride (25 percent; SMCL of 2 mg/L), pH (43 percent above upper limit), chloride (22 percent), and sulfate (22 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (80 percent), pH (43 percent above upper WDEQ Class II limit of 9), TDS (22 percent), chloride (22 percent), sulfate (22 percent), and boron (12 percent; WDEQ Class II standard of 750 µg/L). Concentrations of one constituent and one characteristic were measured at greater than State of Wyoming livestock-use standards: mercury (in one of two samples analyzed for the constituent; WDEQ Class III standard of 0.05 µg/L) and pH (43 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the CBS also was characterized and the quality evaluated on the basis of 72 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram C**). TDS concentrations were variable and indicated that most waters were moderately saline (46 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram C;** supplementary data tables). TDS concentrations ranged from 1,020 to 24,100 mg/L, with a median of 4,730 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (in the two samples analyzed for this constituent), chloride (81 percent), sulfate (36 percent), and pH (22 percent above upper SMCL limit of 8.5 and 2 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the two samples analyzed for this constituent), chloride (94 percent), TDS (82 percent), and sulfate (39 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were chloride (49 percent), TDS (47 percent), pH (22 percent above upper WDEQ Class II limit of 8.5 and 2 percent below lower WDEQ Class II limit of 6.5), and sulfate (3 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 18 percent of produced-water samples.

Medicine Bow Mountains

The chemical composition of groundwater in the Cloverly aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from two wells and one spring. Individual constituent concentrations are listed in **Appendix E4**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 112 to 168 mg/L, with a median of 168 mg/L. On the basis of the characteristics and constituents analyzed, the quality of water from the Cloverly aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Cloverly aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Cloverly aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 3 wells and 10 springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram A**). TDS concentrations were variable and indicated that most waters were fresh (85 percent of samples), and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram A**; supplementary data tables). TDS concentrations ranged from 228 to 2,090 mg/L, with a median of 419 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (46 percent of samples analyzed for the constituent), pH (33 percent above upper limit), fluoride (15 percent), and sulfate (15 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent of samples analyzed for the constituent), sulfate (31 percent), and TDS (8 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the LM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F4**. The TDS concentration (1,200 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not

available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and pH exceeded aesthetic standards for domestic use. One characteristic (pH above upper limit) exceeded State of Wyoming livestock standards. No characteristics or constituents exceeded State of Wyoming agriculture standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Cloverly aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Individual constituent concentrations are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (60 percent of samples), and remaining waters were fresh (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 322 to 1,770 mg/L, with a median of 1,290 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: ammonia (33 percent; WDEQ Class I standard of 0.5 mg/L) and fluoride (20 percent). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (60 percent), fluoride (60 percent), sulfate (60 percent), manganese (33 percent; SMCL of 50 µg/L), and pH (40 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent), boron (60 percent), and sulfate (60 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (40 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the CBN also was characterized and the quality evaluated on the basis of 104 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram E**). TDS concentrations were variable and indicated that most waters were slightly saline (39 percent of samples) and remaining waters ranged from moderately to very saline (**Appendix F5**; **Appendix H3**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,040 to 19,600 mg/L, with a median of 3,730 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (80 percent), sulfate (50 percent), iron (in one of three samples analyzed for this constituent), and pH (10 percent above upper limit and 3 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (88 percent of samples analyzed for the constituent), TDS (77 percent), and sulfate (54 percent). Characteristics and

constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (41 percent), chloride (38 percent), pH (10 percent above upper limit and 3 percent below lower limit), and sulfate (10 percent). The State of Wyoming Class IV standard for TDS was exceeded in 25 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Cloverly aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (385 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Cloverly aquifer in the GP was suitable for most uses. No characteristics or constituents in the Cloverly aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Cloverly aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentrations (9,030 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards. TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards.

7.3.14 Inyan Kara aquifer

The Inyan Kara aquifer consists of the Early Cretaceous Inyan Kara Group and is present only in the Denver-Julesburg Basin (**Plates 1, 2**) (**Plate M**). The Inyan Kara Group has been divided into the upper Fall River Formation and the lower Lakota Formation. The lithostratigraphic unit has been previously referred to and is considered equivalent to the Cloverly Formation (Love and Christiansen, 1985, Sheet 2; Love et al., 1993). The formation is composed of "rusty to light-gray sandstone containing lenticular, chert-pebble conglomerate interbedded with variegated bentonitic claystone" (Love and Christiansen, 1985, Sheet 2). The Inyan Kara Group (identified as the Cloverly Formation) ranges from 0- to 300-ft in thickness in the Denver-Julesburg Basin (Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981). The Inyan Kara Group (identified as the Cloverly Formation) was considered a potential aquifer or minor aquifer by previous investigators (Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981) and consequently, the unit was defined as an aquifer herein (**Plate M**).

7.3.15 Morrison confining unit or Morrison aquifer and confining unit

The physical and chemical characteristics of the Morrison confining unit or Morrison aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Morrison confining unit or Morrison aquifer and confining unit consists of the Late Jurassic Morrison Formation (**Plates J, K, M, S, T, U**), which is present throughout the basins of the PtRB with outcrops present near the uplifts (**Plates 1, 2**). The Morrison Formation consists of interbedded buff, gray, green, maroon, and red shale; clayey siltstone; buff to yellow siltstone; buff to brown, partly calcareous, fine- to medium-grained sandstone; and some thin limestone lenses (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960; Harshman, 1972). The Morrison Formation has a maximum thickness of 325 ft in the Rawlins

Uplift area (Berry, 1960). Reported thickness in the Laramie, Shirley, and Hanna Basins area ranges from 125 to 320 ft (Richter, 1981a, Table IV-1, and references therein). Reported thickness in the Denver-Julesburg Basin ranges from 125 to 320 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 22; Lowry and Crist, 1967, Table 1, p. 10; Libra et al., 1981, Table IV-1, and references therein).

Because of predominantly fine-grained composition and inferred low permeability, the Morrison Formation generally is defined as a regional confining unit (defined herein as the Morrison confining unit) or a regional confining with locally occurring discontinuous sandstone aquifers (defined herein as the Morrison aquifer and confining unit) (**Plates J, K, M, S, T, U**). With the exception of the Denver-Julesburg Basin, the Morrison confining unit or Morrison aquifer and confining unit is overlain by the Cloverly aquifer and underlain by the Sundance aquifer (**Plates J, K, S, T, U**). In the Denver-Julesburg Basin, the Morrison aquifer and confining unit is overlain by the Inyan Kara aquifer and underlain by the Sundance aquifer (**Plate M**).

Previous investigators have noted that discontinuous sandstone beds interbedded with finer-grained rocks in the Morrison confining unit or Morrison aquifer and confining unit will yield small quantities of water to wells adequate only for stock or domestic use where water quality is adequate; water from the hydrogeologic unit likely is too mineralized for many uses in many areas (Robinson, 1956; Burritt, 1962; Crist and Lowry, 1972; Libra et al., 1981; Richter, 1981a; Younus, 1992). Richter (1981a, Table IV-2, p. 51) reported that some "saturated discontinuous basal sandstone lenses had been encountered in petroleum test wells near Medicine Bow." Artesian conditions likely predominate, except in outcrop areas where unconfined (water table) conditions are possible (for example, Robinson, 1956; Burritt, 1962). Very few wells are installed in the Morrison confining unit or Morrison aquifer and confining unit, but available hydrogeologic data, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Morrison confining unit and Morrison aquifer and confining unit likely is from infiltration of precipitation and streamflow at outcrop areas. Robinson (1956) and Burritt (1962) reported that alluvium overlying the Morrison confining unit recharges the unit in parts of the Laramie Basin.

Chemical characteristics

Groundwater quality of the Morrison confining unit or Morrison aquifer and confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E and F**).

Sweetwater Arch

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 315 to 450 mg/L, with a median of 445 mg/L. On the basis of the characteristics and constituents analyzed, the quality of water from the Morrison confining unit or Morrison aquifer and confining unit in the SA was suitable for most uses. No characteristics or constituents in the Morrison confining unit or Morrison aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards on the basis of the environmental water samples.

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the SA also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (4,330 mg/L) indicated

that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in produced-water from the Morrison confining unit or Morrison aquifer and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and chloride exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, upper limit of 8.5, and 250 mg/L, respectively). TDS and chloride exceeded agricultural-use standards (WDEQ Class II standards of 2,000 mg/L and 100 mg/L, respectively). One characteristic (pH above upper WDEQ Class III limit of 8.5) exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of five produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were moderately saline (80 percent of samples), and remaining waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 3,010 to 10,900 mg/L, with a median of 5,170 mg/L.

Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (60 percent), sulfate (60 percent; SMCL of 250 mg/L), and pH (20 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), and sulfate (60 percent; WDEQ Class II standard of 200 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (60 percent; WDEQ Class III standard of 5,000 mg/L), chloride (40 percent; WDEQ Class III standard of 2,000 mg/L), and pH (20 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 20 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (1,030 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the

LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (18,600 mg/L) indicated that the water was very saline. Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards. TDS and chloride exceeded State of Wyoming livestock standards. The WDEQ Class IV standard for TDS was exceeded in the sample.

7.3.16 Sundance aquifer

The physical and chemical characteristics of the Sundance aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Middle and Late Jurassic Sundance Formation, which contains the Sundance aquifer, is present throughout the basins of the PtRB, with outcrops near the uplifts (**Plates 1, 2**) and deeply buried elsewhere. As many as seven members of the Sundance Formation have been described: Windy Hill, Redwater Shale, Pine Butte, Lak, Hulett, Stockade Beaver Shale, and Canyon Springs Members (Pipiringos, 1968; Harshman, 1972). The uppermost Windy Hill Member is a buff to gray, very fine-to medium-grained, thin-bedded, limy oolitic sandstone or a fine-to coarse-grained calcite-cemented sandstone with gray-green to dark-gray shale partings (Pipiringos, 1968; Harshman, 1972). Peterson (1994) reassigned the Windy Hill Member to the basal part of the Morrison Formation, even though this member is a marine unit, whereas most of the Morrison is non-marine. The Redwater Shale Member is greenish or yellowish-gray shale and clayey siltstone with some firmly lime-cemented coquinoid sandstone or sandy coquinoid limestone (Pipiringos, 1968; Harshman, 1972). The Pine Butte Member is greenish white, firmly lime-cemented sandstone with interbedded greenish to yellowish-gray glauconitic siltstone and clay shale (Pipiringos, 1968; Harshman, 1972). The Lak Member is pink to reddish-brown to yellowish-white fine-to medium-grained sandstone, sandy siltstone, and siltstone (Pipiringos, 1968; Harshman, 1972). The Hulett Sandstone Member is fine-to medium-grained, buff to white sandstone with some shale and glauconite (Pipiringos, 1968, Harshman, 1972). The Stockade Beaver Shale Member is greenish-gray to greenish-yellow shale and siltstone (Pipiringos, 1968; Harshman, 1972). The Canyon Springs Member is light gray fine-grained oolitic to yellowish-white fine-to medium-grained sandstone with chert pebbles at the base in some areas (Pipiringos, 1968; Harshman, 1972). The Sundance Formation was deposited in a marine environment and is 195- to 365-ft thick (Pipiringos, 1968).

In the Granite Mountains Uplift and Shirley Basin, the Sundance aquifer is confined from above by the Morrison confining unit and underlain by either the Gypsum Spring confining unit or the

Nugget aquifer (**Plate J**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Goose Egg or Chugwater confining units in the Hartville Uplift and Laramie Mountains (**Plate K**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Chugwater confining unit in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Chugwater aquifer and confining unit (**Plate S**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and underlain by the Jelm aquifer or Chugwater confining unit in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

Despite little information available to describe the hydrogeologic characteristics of the Sundance Formation, all investigators consider all or parts of the lithostratigraphic unit to be an aquifer or potential aquifer, particularly in areas with substantial amounts of sandstone (for example, Berry, 1960; Welder and McGreevy, 1966; Lowry and Crist, 1967; Lowry et al., 1973; Collentine et al., 1981; Richter, 1981a, b). Littleton (1950b) and Robinson (1956) noted that sandstone beds in the unit were aquifers or potential aquifers in the Laramie Basin. In fact, Robinson (1956, p. 41) noted that the unit "lithologically is an excellent aquifer." Richter (1981a, p. 70-71) reported that the Sundance aquifer in the Laramie, Shirley, and Hanna Basins was composed of three "massive permeable sandstone members" separated by impermeable shales and sandstones, resulting in three confined subaquifers hydraulically integrated into one aquifer by faults and fractures. Collentine et al. (1981) defined the Sundance Formation as a "minor aquifer" in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. Both Collentine et al. (1981) and Richter (1981b) stated that the Sundance aquifer is in hydraulic connection with the underlying Nugget aquifer where present. Consequently, these investigators combined the Sundance aquifer and Nugget aquifer into a single aquifer or aquifer system defined as the "Sundance-Nugget aquifer," and that definition is retained herein for the parts of the PtRB where both units occur (**Plates J, S**).

Because of deep burial throughout most of the PtRB, most wells completed in the Sundance aquifer are oil wells and most information describing the hydrogeologic characteristics of the Sundance aquifer are from these types of deep wells. Collentine et al. (1981) noted artesian conditions in wells installed in the Sundance aquifer in the Rawlins Uplift area. In the Laramie, Shirley, and Hanna Basins, Richter (1981a, Table IV-2, p. 50) reported that basal sandstones of the Sundance aquifer have "large intergranular porosity and permeability" and "upper sands are well cemented and have low permeabilities." He reported artesian conditions in the basal sandstones with flows ranging from 1 to 50 gal/min. In parts of the Sundance aquifer (presumably the "upper sands"), primary (intergranular) permeability may be relatively small, but substantially larger in structurally deformed areas with fractures (Richter, 1981a). Hydrogeologic data describing the Sundance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Because of limited outcrop extent and small permeabilities, Richter (1981a, p. 71) speculated that much of the recharge to the Sundance aquifer in the Laramie, Shirley, and Hanna Basins is from interformational flow. Numerous springs and seeps discharge from the Sundance aquifer along the southwestern flank of the Laramie Mountains and northern flank of the Shirley and Freezeout Mountains (Richter, 1981a); reported discharge from these springs generally was less than 1 gal/min. The investigator (Richter, 1981a, p. 71) speculated that these "relatively small [spring] discharges indicate that the rocks have negligible permeabilities because available recharge to the rocks and those elevated areas is relatively large."

Chemical characteristics

Groundwater quality of the Sundance aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics

tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Sundance aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from a spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (680 mg/L) indicated that the water was fresh (TDs concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; USEPA SMCL of 500 mg/L) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Sundance aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations indicated that waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 1,100 to 2,010 mg/L, with a median of 1,910 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: fluoride (50 percent); USEPA MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), fluoride (50 percent; SMCL of 2 mg/L), sulfate (67 percent), and pH (50 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent of samples analyzed for the constituent; WDEQ Class II standard 8), sulfate (67 percent), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), boron (33 percent; WDEQ Class II standard of 750 µg/L), and chloride (33 percent; WDEQ Class II standard of 100 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Sundance aquifer in the CBS also was characterized and the quality evaluated on the basis of 18 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram D**). TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples) and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram D;** supplementary data tables). TDS concentrations ranged from 1,040 to 123,000 mg/L, with a median of 2,240 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality

analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (72 percent), chloride (39 percent; SMCL of 250 mg/L), and pH (35 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (78 percent of samples analyzed for the constituent), sulfate (72 percent), and TDS (61 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (35 percent above upper limit), TDS (17 percent; WDEQ Class III standard of 5,000 mg/L), chloride (17 percent; WDEQ Class III standard of 2,000 mg/L), and sulfate (6 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 11 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Sundance aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentrations (200 and 604 mg/L) indicated that the waters were fresh (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use in one sample. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards in one sample. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Sundance aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 17 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram F**). TDS concentrations were variable and indicated that most waters were slightly saline (65 percent of samples) and remaining waters ranged from moderately saline (3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F5**; **Appendix H3**, **diagram F;** supplementary data tables). TDS concentrations ranged from 1,170 to 16,600 mg/L, with a median of 2,460 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (88 percent), chloride (47 percent), and pH (40 percent above upper SMCL limit of 8.5 and 7 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (88 percent of samples analyzed for the constituent), sulfate (88 percent), and TDS (76 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (40 percent above upper WDEQ Class III limit of 8.5 and 7 percent below lower WDEQ Class III limit of 6.5), TDS (12 percent), chloride (12 percent), and sulfate (12 percent). The State of Wyoming Class IV standard for TDS was exceeded in 6 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Sundance aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (260 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Sundance aquifer in the GP was suitable for most uses. No characteristics or constituents in the Sundance aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Sundance aquifer in the GP also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F6**. TDS concentrations (2,680 and 3,830 mg/L) indicated that most waters were slightly to moderately saline (**Appendix F6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Two characteristics (pH above upper limit in one sample and TDS in both samples) and two constituents (chloride in one sample and sulfate in both samples) exceeded aesthetic standards for domestic use. One characteristic (TDS) and two constituents (chloride and sulfate) exceeded the State of Wyoming agricultural-use standards in both samples. One characteristic (pH above upper limit) exceeded the State of Wyoming livestock-use standards in one sample.

7.3.17 Gypsum Spring confining unit

Composed of an interbedded sequence of shale, siltstone, limestone, dolomite, and gypsum, the Gypsum Spring Formation comprises the Gypsum Spring confining unit (**Plate J**). The hydrogeologic unit was classified as a regional leaky confining unit by Richter (1981b) and the confining unit designation is retained herein. No additional information was located describing the physical and chemical hydrogeologic characteristics of the Gypsum Spring confining unit in the PtRB, so additional description as part of this study was not possible.

7.3.18 Nugget aquifer

The physical and chemical characteristics of the Nugget aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Nugget Sandstone, which contains the Nugget aquifer, is present in the subsurface in parts of the PtRB, with some outcrops occurring near uplifts (**Plates 1, 2**). The Nugget Sandstone is a very fine-to coarse-grained buff to white to pink highly porous sandstone (Pipiringos, 1957, 1968;

Berry, 1960). Pipiringos (1968) also described a lower Bell Springs Member that is red and gray sandstone with red, green, and pale-purplish-red to pale-red siltstone and shale. Pipiringos (1957) noted that the formation may be of eolian and (or) subaqueous origin. Berry (1960) estimated a maximum thickness of 110 ft in the subsurface in the vicinity of the Rawlins Uplift. Richter (1981a, Table IV-2, p. 50, and references therein) reported that the Nugget Sandstone in the Laramie, Shirley, and Hanna Basins area ranged from 50 to 100 ft in thickness. Collentine et al. (1981, Table IV-2, p. 50) reported that the Nugget Sandstone in the Great Divide and Washakie Basins area ranged from 0 to 650 ft or more in thickness.

Early investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of the Nugget aquifer. Collentine et al. (1981) defined the Nugget Sandstone as a "minor aquifer" in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. Both Collentine et al. (1981) and Richter (1981a) stated that the Nugget aquifer is in hydraulic connection with the overlying Sundance aquifer in the Great Divide and Washakie Basins and Laramie, Shirley, and Hanna Basins, respectively. Consequently, these investigators combined the Nugget and Sundance aquifers in these areas into a single aquifer or aquifer system defined as the "Sundance-Nugget aquifer" and that definition is retained herein for the parts of the PtRB where both units occur (**Plates J, S**). The Nugget aquifer is confined from above by the Gypsum Spring confining unit where present or overlain from above by the Sundance aquifer; the unit is confined from below by the Popo Agie confining unit of the Chugwater aquifer and confining unit in the Granite Mountains Uplift, Shirley Basin, and Rawlins Uplift (**Plates J, S**). Hydrogeologic data describing the Nugget aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Because of deep burial throughout most of the PtRB, data describing the hydrogeologic characteristics of the Nugget aquifer primarily are from deep oil wells. In the Laramie, Shirley, and Hanna Basins, Richter (1981a, Table IV-2, p. 50) reported that basal sandstones have "large intergranular porosity and permeability." He reported artesian conditions in "deep basin wells" with flows ranging from 50 to 100 gal/min.

Most studies of the Nugget aquifer within the PtRB are associated with development of the public groundwater supply for the city of Rawlins (Anderson and Kelly, Inc., 1984; James M. Montgomery, Consulting, Engineers, Inc., 1982a, b; 1983a, b; 1986a, b; Western Water Consultants, Inc., 1997, and references therein). Some insight into the hydrogeologic characteristics of the Nugget aquifer is provided by these studies through construction and testing of Rawlins public (municipal) supply wells completed in the aquifer in the Miller Hill area. Anderson and Kelly, Inc. (1984) and James M. Montgomery, Consulting Engineers, Inc. (1982a, b; 1986a, b) described the hydrogeologic characteristics in the area on the basis of three public-supply wells completed in the aquifer. Anderson and Kelly, Inc. (1984) completed a 1,730-ft deep well into the Nugget aquifer. They noted that water flowed from the well at 350 gal/min from a thin zone in the upper part of the Nugget Sandstone. Subsequently, James M. Montgomery Consulting Engineers (1986a, b) completed two additional wells to a similar depth in the same area. Like Anderson and Kelly, Inc. (1984), the investigators noted that groundwater flow to the wells was primarily from thin discrete zones within the Nugget Sandstone. Aquifer tests were conducted at all three wells using both constant-drawdown and recovery methods. They reported that the aquifer was "highly productive" in the area. Based on conditions encountered during drilling and subsequent aquifer tests, James M. Montgomery Consulting Engineers (1986a, b) concluded that localized fracture zones (and therefore, secondary permeability) are responsible for most of the water yielded to wells completed in the Nugget aquifer in the Miller Hill area. They stated that the localized fracture zones are not present throughout the formation.

In their study of the Nugget aquifer in the vicinity of Miller Hill, Anderson and Kelly, Inc. (1984, p. 19) speculated that recharge to the Nugget aquifer occurs in three ways: direct infiltration of precipitation on outcrops; infiltration

from perennial streamflow losses from McKinney, Littlefield, and Sage Creeks on outcrops; and interformational movement. They noted that recharge from direct infiltration of precipitation on outcrops is likely small because of limited Nugget aquifer outcrop in the study area. The investigators (Anderson and Kelly, Inc., 1984, p. 19) did not quantify recharge but they stated that "the opportunities for recharge are extensive" and the "good water quality of the Nugget well suggest a relatively active groundwater circulation system."

Chemical characteristics

Groundwater quality of the Nugget aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Nugget aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L) (67 percent of samples) and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,080 to 4,710 mg/L, with a median of 1,150 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL of 500 mg/L), sulfate (67 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (67 percent of samples analyzed for the constituent; WDEQ Class II standard 100 mg/L), sulfate (67 percent; WDEQ Class II standard of 200 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). One characteristic and one constituent in produced-water samples were measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5) and chloride (33 percent; WDEQ Class III limit of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Nugget aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 596 to 913 mg/L, with a median of 673 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations

of two characteristics exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent) and pH (100 percent above upper limit).

For agricultural and livestock use, concentrations of one characteristic exceeded State of Wyoming standards in the CBS. Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (100 percent above upper limit). No characteristics or constituents exceeded State of Wyoming agricultural standards.

The chemical composition of groundwater in the Nugget aquifer in the CBS also was characterized and the quality evaluated on the basis of 16 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram E**). TDS concentrations were variable and indicated that most waters were moderately saline (62 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,900 to 16,000 mg/L, with a median of 4,900 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (88 percent), iron (in one of two samples analyzed for this constituent; SMCL of 300 µg/L), sulfate (36 percent), and pH (21 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent), TDS (94 percent), iron (in one of two samples analyzed for this constituent; WDEQ Class II standard of 5,000 µg/L), sulfate (36 percent), and pH (7 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were chloride (56 percent), TDS (44 percent; WDEQ Class III standard of 5,000 mg/L), and pH (21 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 19 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Nugget aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (1,770 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. Sulfate exceeded State of Wyoming agricultural standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.19 Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit

The physical and chemical characteristics of the Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Jelm aquifer is composed of the Late Triassic Jelm Formation (**Plates T, U**). The Chugwater confining unit and Chugwater aquifer and confining unit are composed of the Permian and Triassic Chugwater Group or Formation and its various formations or members (**Plates J, K, M, S, T, U**). These lithostratigraphic units are present at or near land surface around most uplifts and throughout the subsurface of the PtRB (**Plates 1, 2**). Historically, the "Jelm" has been considered part of the Chugwater Group or Formation in some areas of the PtRB; in other areas, it has been mapped and described separately. The "Chugwater" has been assigned both formation and group rank; the unit has been divided into as many as five formations or members (Jelm Formation; Popo Agie Formation or Member, Crow Mountain Sandstone or Sandstone Member, Alcova Limestone or Limestone Member, and Red Peak Formation or Member), depending on rank of the lithostratigraphic unit assigned by different investigators in a given area of the PtRB. Some formations or members of the "Chugwater," where the lithostratigraphic unit is divided, are missing locally due to erosion or nondeposition.

The Jelm Formation was included in the Chugwater Group by Pipiringos (1968). He also divided it into the Sips Creek and Red Draw Members. The Sips Creek Member is a greenish-white to reddish-brown and yellow sandstone that is in part conglomeratic with pebbles of siltstone, limestone, and shale, and fragments of fossil wood and bone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). The upper part of the Sips Creek Member is a reddish-brown siltstone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). In the Shirley Basin, the Sips Creek Member is a tan to buff well-cemented sandstone (Harshman, 1972). It is a fluvial and lacustrine deposit (Pipiringos and O'Sullivan, 1978) that is 0- to 315-ft thick (Pipiringos, 1968). The Red Draw Member is reddish-brown shale, siltstone, and sandstone that is interbedded with some greenish-gray siltstone (Pipiringos, 1968; Harshman, 1972; Pipiringos and O'Sullivan, 1978). It is a fluvial deposit (Pipiringos and O'Sullivan, 1978) that is 0- to 140-ft thick (Pipiringos, 1968). The undivided Jelm Formation is as much as 360-ft thick (Pipiringos, 1968).

Where undivided and assigned formation rank, the Chugwater Formation is described as red shale and sandstone, with some purple, pink, green, and buff beds, and a few limestone and gypsum beds (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960). It is of fluvial, lacustrine, eolian, and marine origin (Pipiringos and O'Sullivan, 1978). The maximum thickness noted by Dobbin, Hoots, et al. (1929) is 1,350 ft.

Where divided into formations or members, the uppermost formation or member of the Chugwater Group or Formation is the Popo Agie Formation or Member (**Plates J, S**). The Popo Agie Formation is a purple to pale-red to ochre siltstone, analcime-rich claystone, silty claystone, and grayish-yellow sandstone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). North and west of the Ferris Mountains, the Popo Agie Formation is divided into the Lyons Valley and Brynt Draw Members (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). It is a fluvial and lacustrine deposit (Pipiringos and O'Sullivan, 1978). The formation ranges from 0- to about 100-ft thick (Pipiringos, 1968).

The next formation or member of the Chugwater Group or Formation is the Crow Mountain Sandstone or Sandstone Member (Pipiringos, 1968) (**Plates J, S**). In the area southeast of the Granite Mountains, the name Crow Mountain was replaced with Jelm by Pipiringos (1968). The upper part of the Crow Mountain Sandstone is white to reddish-brown sandstone and siltstone with minor amounts of pale-red and green shale (Pipiringos and O'Sullivan, 1978). The lower part of the unit is salmon-red to reddish-brown sandstone with minor amounts of sandstone, siltstone, and some sandy clay shale (Pipiringos and O'Sullivan, 1978). The upper part is of fluvial origin, whereas the lower part is of marine origin

(Pipiringos and O'Sullivan, 1978). Pipiringos (1968, p. D11) showed a section that is 192-ft thick.

The next unit, the Alcova Limestone or Limestone Member (**Plates J, K, S**), is identified as part of the Chugwater Group or Formation by some investigators (Pipiringos, 1968; Harshman, 1972; Pipiringos and O'Sullivan, 1978) and as a member of the Crow Mountain and Jelm Formations by others (High and Picard, 1969). It is a gray, purple, greenish-gray, brownish-gray, and greenish-brown limestone that is sandy in its upper and lower parts (Harshman, 1972; Pipiringos and O'Sullivan, 1978). The Alcova Limestone is resistant and commonly forms prominent hogbacks. It is of marine origin (Pipiringos and O'Sullivan, 1978). The formation is missing locally due to erosion or nondeposition. Where present, it has a maximum thickness of 20 ft (High and Picard, 1969).

The Red Peak Formation or Member is the lowest unit of the Chugwater Group or Formation (Pipiringos, 1968) (**Plates J, K, S**). It is a pale to moderate reddish-brown to red siltstone with some interbedded thin yellowish-gray to white to pink, very fine-to fine-grained calcareous sandstone (Harshman, 1972; Lowry et al., 1973; Pipiringos and O'Sullivan, 1978). It is of marine origin (Pipiringos and O'Sullivan, 1978). Lowry et al. (1973) reported a thickness of 600 to 700 ft.

The Jelm aquifer is overlain by the Sundance aquifer and underlain by the Chugwater confining unit (**Plates T, U**). Little hydrogeologic information describing the Jelm aquifer could be located, but available hydrogeologic data describing the Jelm aquifer, including well-yield and other hydraulic properties, are summarized in **Plate 3**. Littleton (1950b, Table 1, p. 14) reported that the unit "may contain artesian water" in the Laramie Basin. Saulnier (1968) reported locally permeable zones in the north flank of the Medicine Bow Mountains and Pass Creek Basin area. Richter (1981a, Table IV-2, p. 50) noted that artesian conditions in basal sandstone and conglomerate of the Jelm aquifer in the Laramie, Shirley, and Hanna Basins could produce flows of 10 to 25 gal/min.

Regionally, most investigators consider the Chugwater Group or Formation to be a confining unit; however, locally permeable sandstones interbedded with low-permeability fine-grained lithologic units (shale, siltstone, limestone) occur throughout the unit, and wells commonly are completed in these sandstones throughout the PtRB. Consequently, the "Chugwater" may be considered a sequence of rocks that regionally functions as both aquifer and confining unit (**Plates J, K, M, S, T, U**), depending upon location examined and the scale of the study. In the Granite Mountains Uplift and Shirley Basin, the Chugwater aquifer and confining unit is overlain by the Nugget aquifer and underlain by either the Phosphoria aquifer and confining unit or the Dinwoody confining unit (**Plate J**). The Chugwater confining unit is overlain by the Sundance aquifer and underlain by the Forelle Limestone in the Hartville Uplift and Laramie Mountains (**Plate K**). The Chugwater confining unit is overlain by the Sundance aquifer and underlain by the Forelle Limestone in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Chugwater aquifer and confining unit is overlain by the Nugget aquifer and underlain by the Goose Egg confining unit (**Plate S**). The Chugwater confining unit is overlain by the Sundance and Jelm aquifers and underlain by the Goose Egg confining unit and Forelle Limestone in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

Classification and reported hydrogeologic characteristics of the "Chugwater" varies by geographic region. In the WRB and Granite Mountains area, Richter (1981b, Table IV-1) classified the Popo Agie Formation and Alcova Limestone as confining units and the Crow Mountain and Red Peak Formations as aquifers/subaquifers; that classification is retained herein (**Plate J**). The Chugwater Group or Formation also is divided into these four lithostratigraphic units in the Rawlins Uplift, so the hydrogeologic unit classification of these four units by Richter (1981b) is retained for this geographic area as well (**Plate S**). The Crow Mountain and Red Peak aquifers/subaquifers may yield small quantities of water to wells and springs at some locations in the WRB and Granite Mountains area (Richter, 1981b). In the Rawlins Uplift area, Berry (1960, p. 17) reported that no known wells were completed in the Chugwater Formation in the area although

"sandstone beds probably will yield small domestic and stock supplies," but then noted that "the water would probably be highly mineralized." Crist and Lowry (1972, p. 53) classified the Chugwater Group as a "low-yield aquifer" in Natrona County. Welder and McGreevy (1966, Sheet 3) reported that "groundwater possibilities were not known, but probably poor" in the Great Divide and Washakie Basins. Collentine et al. (1981) defined the Chugwater Formation as an "aquitard" and "confining unit" in the Great Divide and Washakie Basins, separating the overlying "Sundance-Nugget aquifer" from the underlying "Paleozoic aquifer system." Similarly, Richter (1981a) defined the Chugwater Formation as a regional leaky confining unit with locally permeable sandstones and fractured limestone interbeds in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plate K**). He also noted that basal sandstones were "water-bearing" in the Laramie Basin, but well yields were small (less than 10 gal/min) and waters were mineralized. Johnson (1994) and Johnson and Huntoon (1994) classified the Alcova Limestone and the Chugwater Formation as confining units in the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains (**Plate J**). Younus (1992, Figure 11, p. 25) classified the Chugwater Formation as a confining unit in the southern Laramie Basin and western flank of the Laramie Mountains, but the investigator noted that sandstone beds may yield mineralized water and may be classified as local aquifers. Sandstones in the Chugwater confining unit locally provide water to numerous wells in the Laramie Basin, primarily for stock and limited domestic uses (for example, Morgan, 1947; Robinson, 1956; Burritt, 1962; Lundy, 1978; Younus, 1992; Mazor, 1990; Mazor et al., 1993). Hydrogeologic data describing the Chugwater confining unit or Chugwater aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

7.3.19.1 Jelm aquifer

Sweetwater Arch

The chemical composition of groundwater in the Jelm aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (1,840 mg/L) indicated that the water was slightly saline (TDS concentrations less than or equal to 999 mg/L). Concentrations of some characteristics and constituents in water from the Jelm aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but two characteristics (pH upper limit and TDS; USEPA SMCLs of 8.5 and 500 mg/L, respectively) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent exceeded State of Wyoming agricultural-use standards: sulfate (WDEQ Class II standard of 200 mg/L). One characteristic exceeded State of Wyoming livestock standards: pH (upper WDEQ Class III limit of 8.5).

Medicine Bow Mountains

The chemical composition of groundwater in the Jelm aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water

sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (492 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Jelm aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Jelm aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.19.2 Chugwater confining unit and Chugwater aquifer and confining unit

Sweetwater Arch

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the SA was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and three springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that waters were fresh (50 percent of samples) to slightly saline (50 percent of samples) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 264 to 2,440 mg/L, with a median of 1,500 mg/L.

Concentrations of some characteristics and constituents in water from the Chugwater confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L) and strontium (in the one sample analyzed for this constituent, the concentration exceeded the USEPA HAL of 4,000 µg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (75 percent) and sulfate (75 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (75 percent of samples analyzed for the constituent) and TDS (50 percent; WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (442 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater aquifer and confining unit in the CBS was suitable for most uses. No characteristics or constituents in the Chugwater aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Chugwater confining unit in the MBM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (314 mg/L) indicated that the water was fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater Group or Formation in the MBM was suitable for most uses. No characteristics or constituents in the Chugwater Group or Formation approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Chugwater confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 13 wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram B**). TDS concentrations were variable and indicated that most waters were slightly saline (78 percent of samples) and remaining waters were fresh (**Appendix E5**; **Appendix G3**, **diagram B**; supplementary data tables). TDS concentrations ranged from 456 to 2,890 mg/L, with a median of 1,550 mg/L.

Concentrations of some characteristics and constituents in water from the Chugwater confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed MCL, but did not exceeded the alternative MCL). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (94 percent of samples analyzed for the constituent), sulfate (94 percent), pH (9 percent below lower SMCL limit of 6.5), and fluoride (9 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent) and TDS (33 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (9 percent below lower WDEQ Class III limit of 6.5).

Central Wyoming basins (north)

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (2,830 and 3,760 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Chugwater aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS (both samples), chloride (one sample; SMCL of 250 mg/L), and sulfate (both samples) exceeded aesthetic standards for domestic use. In both samples, TDS, chloride (WDEQ Class II standard of 100 mg/L), and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Chugwater confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (436 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater confining unit in the GP was suitable for most uses. No characteristics or constituents in the Chugwater confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.19.2.1 Alcova confining unit within Chugwater aquifer and confining unit

Sweetwater Arch

The chemical composition of groundwater in the Alcova confining unit within of Chugwater aquifer and confining unit in the SA was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentrations (304 and 453 mg/L) indicated that the waters were fresh (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Alcova confining unit within of Chugwater aquifer and confining unit in the SA was suitable for most uses. No characteristics or constituents in the Alcova confining unit within of Chugwater aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Alcova confining unit within of Chugwater aquifer and confining unit in the LM was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentrations (628 and 648 mg/L) indicated that the waters were fresh (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Alcova confining unit within of Chugwater aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS in both samples) and one constituent (sulfate in one sample) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards in both samples. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.20 Goose Egg confining unit and Goose Egg aquifer and confining unit

The physical and chemical characteristics of the Goose Egg confining unit and Goose Egg aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Goose Egg confining unit and Goose Egg aquifer and confining unit consists of the Permian and Early Triassic Goose Egg Formation. Lithology of the Goose Egg Formation is highly variable and consists of a sequence of gypsum, anhydrite, limestone, dolomite, and moderately reddish-orange siltstone and shale (Maughan, 1964; Harshman, 1972). The formation has been divided into numerous members that differ by location. In places, the Opeche Shale and the Minnekahta Limestone are considered members of the Goose Egg Formation (Love and Christiansen, 1985, Sheet 2). The rocks were deposited in a marginal marine environment with high salinity and a warm arid climate, such as a vast shallow lagoon or tidal flat (Maughan, 1964). At the type location in Natrona County, the Goose Egg Formation is as much as 380-ft thick (Burk and Thomas, 1956).

Regionally, most investigators consider the Goose Egg Formation to be a confining unit; however, locally permeable discontinuous sandstones interbedded with low-permeability fine-grained lithologic units (shale, siltstone, limestone) occur throughout the formation. Consequently, the Goose Egg Formation, like the equivalent Phosphoria Formation and overlying Chugwater Group or Formation with very similar hydrogeologic characteristics, may be considered a sequence of rocks that regionally functions as both aquifer and confining unit (**Plates J, K, S, T, U**), depending upon location examined and the scale of the study. In the Granite Mountains and Shirley Basin, the Goose Egg aquifer and confining unit is overlain by the Chugwater aquifer and confining unit and underlain by the Casper aquifer (**Plate J**). The Goose Egg confining unit is overlain by the Sundance aquifer and underlain by the Hartville and Casper aquifers in the Hartville Uplift and Laramie Mountains (**Plate K**). In the Rawlins

Uplift, the Goose Egg aquifer and confining unit is overlain by the Chugwater aquifer and confining unit and underlain by the Tensleep aquifer (**Plate S**). The Goose Egg confining unit is overlain by the Chugwater confining unit and underlain by the Tensleep aquifer in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley (**Plate T**). In the Hanna and Laramie Basins, the Goose Egg confining unit is overlain by the Chugwater confining unit and underlain by the Casper aquifer (**Plate U**).

Gypsum and anhydrite in interbeds and fractures in shales and siltstones of the Goose Egg Formation (and associated members, including the Opeche Shale) contribute to the overall confining characteristics of the unit. In the south-central edge of the Powder River Basin in the vicinity of Douglas, Garland (1996) found that gypsum and anhydrite enhanced overall ductility of the Goose Egg confining unit, allowing the unit to effectively confine and maintain hydraulic integrity of the underlying Casper aquifer in areas with widespread extensional fractures associated with Laramide folds and faults.

Most wells completed in the unit are low yielding (less than 20 gal/minute). Low-yielding wells are completed in the discontinuous and primarily confined sandstones of the Goose Egg confining unit and Goose Egg aquifer and confining unit throughout the PtRB. In addition, locally occurring fractured limestone interbeds also may be permeable (Richter, 1981a, Table IV-2). Stacy (1994) and Stacy and Huntoon (1994) noted that saturated limestone interbeds "form minor aquifers" within the Goose Egg confining unit in the Casper Mountain area at the northwestern flank of the Laramie Mountains. Larger well yields may be possible where secondary porosity and permeability (primarily fractures) have developed in areas with deformation (folds and faults) (Lowry et al., 1973; Richter, 1981a, Table IV-2; Stacy, 1994; Stacy and Huntoon, 1994). Wells completed in the unit are used primarily for stock purposes due to generally small well yield and poor groundwater quality. In the Rawlins Uplift area, Berry (1960, p. 16) reported that "small quantities of highly mineralized water" probably could be obtained from "permeable materials" in the Goose Egg Formation (identified as "undifferentiated rocks" of Permian age). Crist and Lowry (1972, p. 53) classified the Goose Egg Formation as a "low-yield aquifer" in Natrona County. Richter (1981a) defined the Goose Egg Formation as a regional leaky confining unit with locally permeable sandstones and fractured limestone interbeds in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plate K**). He also noted that the "locally scattered permeable and fractured limestone interbeds yield minor quantities (1 to 15 gal/min) of water to wells." Hydrogeologic data describing the Goose Egg confining unit and Goose Egg aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Goose Egg confining unit and Goose Egg aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Goose Egg aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (86 percent of samples) and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 1,090 to 3,220 mg/L, with a median of 2,430 mg/L.

Concentrations of some characteristics and constituents in water from the Goose Egg aquifer

and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon (in one of two samples analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), strontium (in both of the samples analyzed for this constituent, the concentration exceeded the USEPA HAL of 4,000 µg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L) and sulfate (100 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), TDS (86 percent; WDEQ Class II standard of 2,000 mg/L), boron (33 percent; WDEQ Class II standard of 750 µg/L), and chloride (14 percent; WDEQ Class II standard of 100 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Goose Egg confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as seven wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram C**). TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples) and remaining waters were moderately saline (**Appendix E5**; **Appendix G3**, **diagram C**; supplementary data tables). TDS concentrations ranged from 1,030 to 3,220 mg/L, with a median of 2,650 mg/L.

Concentrations of some characteristics and constituents in water from the Goose Egg confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic (TDS, 100 percent of samples analyzed for the constituent) and one constituent (sulfate, 100 percent) always exceeded aesthetic standards for domestic use.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. One characteristic (TDS, 92 percent of samples analyzed for the constituent) and one constituent (sulfate, 100 percent) in environmental water samples were measured at concentrations greater than agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.21 Dinwoody confining unit

The physical and chemical characteristics of the Dinwoody confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Dinwoody confining unit is composed of the Early Triassic Dinwoody Formation (**Plate J**). The Dinwoody Formation was described by Pipiringos and O'Sullivan (1978) as gray to olive-gray siltstone and shale with thin brown limestone beds near the base of this marine unit. In the Wind River Basin (WRB) and Granite Mountains, Richter (1981b, Table IV-1, and references therein) defined the Dinwoody Formation as a confining unit because the unit is composed of generally impermeable interbedded sandy dolomitic siltstone, calcareous sandstone, and thin dolomite and limestone; the investigator reported that the unit was as much as 250-ft thick. Few wells are known to be completed in the Dinwoody confining unit, and little information was located describing the physical and chemical hydrogeologic characteristics of the Dinwoody confining unit in the PtRB.

Chemical characteristics

The chemical composition of groundwater in the Dinwoody confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (6,600 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Dinwoody confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively) and State of Wyoming agricultural- and livestock-use standards (WDEQ Class II standards of 2,000 and 200 mg/L, respectively, and WDEQ Class III standards of 5,000 and 3,000 mg/L, respectively).

7.4 Paleozoic hydrogeologic units

Paleozoic hydrogeologic units (aquifers and confining units) are described in this section of the report. Paleozoic hydrogeologic units underlie much of the PtRB, but due to deep burial and highly mineralized groundwater unsuitable for most uses throughout most of their extent in the subsurface, they generally can be used only along mountain-basin margins where they crop out and are directly exposed at land surface or immediately downgradient in adjacent bordering structural basins where they occur at shallow depths below younger hydrogeologic units. In addition, permeability decreases and groundwater quality deteriorates rapidly downgradient from outcrop areas along the basin margins. Consequently, most wells in Paleozoic hydrogeologic units have been installed for oil and gas production, commonly at thousands of feet below land surface.

Permeability and groundwater circulation in Paleozoic hydrogeologic units is controlled by lithology, sedimentary structure and depositional environment, and tectonic structures such as folds and faults (Lundy, 1978; Huntoon and Lundy, 1979b; Thompson, 1979; Eisen et al., 1980; Richter, 1981a, b; Western Water Consultants, Inc., 1982, 1993, 1995; Davis, 1984; Huntoon, 1985, 1993; Wiersma, 1989; Younus, 1992; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; WWC Engineering, 2006a, b). The predominant lithologies of the lithostratigraphic units composing Paleozoic hydrogeologic units are sandstone, carbonates (limestone and dolomite), and shale. Primary porosity and intergranular permeability are much greater in the sandstones than in the carbonates and shale, where primary permeability is very low. Carbonate aquifers generally may be utilized only in areas where substantial secondary permeability is developed, most commonly in areas of structural deformation (for example, anticlines) and its associated faults and fractures.

As described herein and by earlier studies, water quality of aquifers contained in Paleozoic hydrogeologic units varies greatly (for example, Lundy, 1978; Huntoon and Lundy, 1979b; Thompson, 1979; Eisen et al., 1980; Richter, 1981a, b; Western Water Consultants, Inc., 1982, 1993, 1995; Davis, 1984; Huntoon, 1985, 1993; Wiersma, 1989; Mazor, 1990; Mazor et al., 1993; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; WWC Engineering, 2006a, b). Recharge to these units generally occurs where the aquifers crop out, although severing by faults near basin margins may disrupt basinward aquifer continuity and prevent much of this recharge from entering the aquifers downgradient from outcrop areas. Near recharge areas, water in these hydrogeologic units can be relatively fresh and may be suitable for most uses. This is where most domestic, stock, or public-supply wells are completed. Elsewhere, and with increasing depth (as indicated by co-produced oil and gas water samples) and as the water moves away from the outcrop, the water can have TDS concentrations several times that of seawater and is not suitable for most uses or is only marginally

suitable for some uses. Where deeply buried, only oil or gas wells are completed in Paleozoic hydrogeologic units.

In parts of the PtRB, some Paleozoic hydrogeologic units possess sufficient hydraulic connection to comprise a regional aquifer system, generally referred to as the Paleozoic aquifer system (**Plates K, M**). The Paleozoic aquifer system is present in the Hartville uplift area, and along the flanks of the Casper Arch and Laramie Mountains and adjacent structural basins. The Paleozoic aquifer system includes some of the most important Paleozoic aquifers in the PtRB. Depending on location and depth, wells completed in the aquifers produce highly variable quantities and quality of water. Except near outcrops, where water-table (unconfined) conditions may be encountered, groundwater in the Paleozoic aquifer system is generally semiconfined or confined. With the exception of wells utilized for hydrocarbon (oil and gas) production, most wells completed in the Paleozoic aquifer system in the PtRB are located in or near outcrops along basin margins or along basin margins where drilling depths are shallow and economical, water quality and aquifer permeability are sufficient for intended uses, and the aquifer is located close to the population center.

7.4.1 Minnekahta Limestone

Present only in the Hartville Uplift and adjacent areas, the Permian Minnekahta Limestone consists of 0- to 40-ft thick yellow, pink, purple, and blue thin-bedded limestone and silty limestone (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). Locally, the Minnekahta Limestone may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). The Minnekahta Limestone is overlain by the Chugwater confining unit and underlain by the Opeche confining unit (**Plate K**). Little information is available describing the physical and chemical hydrogeologic characteristics of this lithostratigraphic unit, but the unit likely yields little to no water (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). No additional information was located describing the physical and chemical hydrogeologic characteristics of the Minnekahta Limestone in the PtRB, so additional description as part of this study was not possible.

7.4.2 Opeche confining unit

Present only in the Hartville Uplift and adjacent areas, the Opeche confining unit is composed of the Permian Opeche Shale (**Plate K**). The Opeche Shale consists of 0- to 120-ft thick red silty shale with some yellow to red sandstone; geodes and thin lenses of purple, red, and gray chert also are present (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). Gypsum interbeds also may be present (Richter, 1981a, Table IV-2, p. 49, and references therein). Locally, the Opeche Shale may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). The Opeche confining unit is overlain by the Minnekahta Limestone and underlain by the Hartville aquifer (**Plate K**). The unit yields little to no water and is considered a confining unit (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Richter, 1981a, Table IV-2, p. 49).

7.4.3 Phosphoria aquifer and confining unit

The physical and chemical characteristics of the Phosphoria aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

Present only in the small part of the southeastern Wind River Structural Basin (WRB) contained within the PtRB, and Granite Mountains area, the Phosphoria aquifer and confining unit consists of the Permian Phosphoria Formation (also defined as the Park City Formation in some areas) (**Plate J**). The Phosphoria Formation ranges from 150 to 350 ft in thickness and is composed of interbedded, dense limestone, dolomite, siltstone, fine-grained sandstone, chert, and phosphatic shale (McKelvey et al., 1959; Richter, 1981b, Table IV-1, and references therein).

With the exception of petroleum exploration, very few wells are installed in the Phosphoria aquifer and confining unit. Development is limited to low-yield wells located along the basin margin where the formation crops out and drilling depths are

shallow. Most information describing the formation composing the aquifer and confining unit comes from petroleum exploration.

The complex intertonguing and interfingering relation between carbonate facies, siltstone facies, and shale and evaporate facies in the Phosphoria aquifer and confining unit creates numerous small, permeable zones that can function as individual confined aquifers (or subaquifers). Consequently, the Phosphoria aquifer and confining unit can be considered a sequence of rocks that functions as both aquifer (primarily sandstone sequences) and confining or leaky confining unit (siltstone, evaporite, and shale sequences) (**Plate J**). These subaquifers may be hydraulically connected by faults and fractures (Richter, 1981b). Primary permeability is generally small, but aquifer permeability may be substantially enhanced where faults and fractures are present, especially near mountain-basin margins such as along the Wind River Mountains (Richter, 1981b).

Recharge to the Phosphoria aquifer and confining unit is likely from infiltration of precipitation and streamflow at outcrop areas and possibly interformational flow. Discharge from these units is likely to seeps, springs, streams, and interformational movement (Whitcomb and Lowry, 1968; Richter, 1981b). Well-yield and spring-discharge measurements and other hydraulic properties for the Phosphoria aquifer and confining unit are summarized on **Plate 3**; these data are from wells or drill-stem tests associated with petroleum exploration.

Chemical composition

Groundwater-quality data are presented and described for the Phosphoria aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix F**).

Sweetwater Arch

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of 35 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, **diagram A**). TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (74 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F1**; **Appendix H1**, **diagram A;** supplementary data tables). TDS concentrations ranged from 1,480 to 21,800 mg/L, with a median of 4,880 mg/L.

Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), chloride (37 percent; SMCL of 250 mg/L), and pH (22 percent above upper SMCL limit of 8.5 and 6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 200 mg/L), TDS (91 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (83

percent; WDEQ Class II standard of 100 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (49 percent; WDEQ Class III standard of 5,000 mg/L), sulfate (40 percent; WDEQ Class III standard of 3,000 mg/L), pH (22 percent above upper WDEQ Class III limit of 8.5 and 6 percent below lower WDEQ Class III limit of 6.5), and chloride (3 percent; WDEQ Class III limit of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 9 percent of produced-water samples.

Central Wyoming basins (south)

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram F**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples) and remaining waters ranged from slightly to very saline (**Appendix F2**; **Appendix H2**, **diagram F;** supplementary data tables). TDS concentrations ranged from 1,610 to 16,400 mg/L, with a median of 8,080 mg/L.

Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (91 percent), chloride (82 percent), and pH (11 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (91 percent of samples analyzed for the constituent), TDS (82 percent), chloride (82 percent), and pH (11 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (64 percent), chloride (36 percent), sulfate (27 percent), and pH (11 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 27 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (22,500 mg/L) indicated that the water was very saline. Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural- and livestock-use standards. The State of Wyoming Class IV standard for TDS was exceeded in the produced-water sample.

7.4.4 Forelle Limestone

The physical and chemical characteristics of the Forelle Limestone in the PtRB are described in this section of the report.

Physical characteristics

The Late Permian Forelle Limestone is present throughout much of the PtRB (**Plates 1, 2; Plates K, M, T, U**). Most available information describing the geologic and hydrogeologic characteristics of the Forelle Limestone is from the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie. The Forelle Limestone consists of thinly bedded, gray, purple, tan, and purple limestone with locally interbedded thin red shales and siltstones; the formation may locally be brecciated and contain gypsum and anhydrite (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Howe, 1970; Lundy, 1978; Richter, 1981a). Locally, the Forelle Limestone may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). In the vicinity of the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie, the Forelle Limestone ranges from 9 to 25 ft in thickness (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Howe, 1970; Lundy, 1978). The Forelle Limestone is overlain by the Chugwater confining unit and underlain by the Satanka confining unit (**Plates K, M, T, U**).

The hydrogeology of the Forelle Limestone has not been evaluated in most locations of the PtRB. In the Laramie Basin, the Forelle Limestone often is grouped with the overlying Chugwater confining unit and underlying Satanka confining unit to collectively describe the hydrogeologic unit as one of several hydrogeologic units that confine the underlying Casper aquifer (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Mazor et al., 1993). Collectively, this group of hydrogeologic units that confine the underlying Casper aquifer were informally named the "Permo-Triassic redbeds" by Huntoon and Lundy (1979a) or "redbeds groundwater system/ confining unit" by Mazor (1990) and Mazor et al. (1993) (**Plates K, U**) because of the distinctive red color of rocks (redbeds) common to these units. Consequently, the Forelle Limestone has been classified as a confining unit in some studies (**Plates K, U**) (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Richter, 1981a; Mazor, 1990; Younus, 1992; Mazor et al., 1993).

A few investigators have reported limited water-development potential for the Forelle Limestone in the Laramie Basin. In the city of Laramie, Morgan (1947) reported that a few wells completed in the Forelle Limestone produced water from the lower part of the formation. Similarly, Robinson (1956) observed that some wells on the western outskirts of Laramie obtained at least part of their water from the Forelle Limestone. In the southern Laramie Basin, Burritt (1962, p. 44) noted that the "Forelle may contain some water, but it is unimportant in the overall groundwater situation of the area," presumably because of the large quantities of water available from the Casper aquifer in the area.

More recently, WWC Engineering (2006a, p. 9-5 to 9-8) conducted a limited evaluation of the potential for the Forelle Limestone, in combination with the lower part of the Chugwater Formation and upper part of the underlying Satanka Shale, to provide water for irrigation of green spaces in Laramie city limits. The investigators reported on several wells in Laramie that obtain water either completely from the Forelle Limestone, or in combination with lower parts of the overlying Chugwater Formation. The investigators noted that recharge to the Forelle Limestone likely was from infiltration on outcrops and possibly vertical leakage from_underlying hydrogeologic units with higher hydraulic heads (Casper aquifer and Satanka confining unit). The investigators (WWC Engineering, 2006a, p. 9-7) noted that the "primary discharge point for the Forelle Limestone occurs in the area between the south end of 30th Street and Huck Finn Pond" because "this area represents the lowest elevation of Forelle Limestone outcrops for over 13 miles to the south and 5 miles to the north." The investigators also noted discharge from the Forelle Limestone to Spring Creek, to springs that supply Huck Finn Pond, and to Warren Spring. Overall, based on the limited information obtained from this evaluation, the investigators concluded that the Forelle Limestone

has potential for water-supply development, at least in some areas within Laramie city limits. Consequently, based on this limited information, the Forelle Limestone was tentatively classified herein as an aquifer only in the Laramie Basin (**Plate U**).

Chemical composition

Groundwater-quality data are presented and described for the Forelle Limestone in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Forelle Limestone in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (216 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Forelle Limestone in the SA was suitable for most uses. No characteristics or constituents in the Forelle Limestone approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Forelle Limestone in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (73,400 and 76,900 mg/L) indicated that the waters were briny (TDS concentrations greater than 34,999 mg/L). Concentrations of some characteristics and constituents in water from the Forelle Limestone in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural- and livestock-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively, and WDEQ Class III standards of 5,000 mg/L, 2,000 mg/L, and 3, 000 mg/L, respectively) in both samples. The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

7.4.5 Satanka confining unit

The physical and chemical characteristics of the Satanka confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Satanka confining unit is composed of the Early Permian Satanka Shale, a lithostratigraphic unit present throughout much of the PtRB (**Plates 1, 2; Plates K, M, T, U**). Most available information describing the geologic and hydrogeologic characteristics of the Satanka Shale are from the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie. The Satanka Shale consists primarily of red shale and silty shale, siltstone, thin interbedded fine-grained sandstone beds, and locally occurring gypsum and anhydrite beds (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Benniran, 1970; Lundy, 1978). In the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of

Laramie, the Satanka Shale ranges from 140 to 338 ft in thickness (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Benniran, 1970; Lundy, 1978).

Many detailed studies of the Casper aquifer in the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie have examined hydrogeologic characteristics of the overlying Satanka Shale; these studies clearly indicate the Satanka Shale is a confining unit, even in fractured areas (for example, Robinson, 1956; Burritt, 1962; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Despite being classified as a confining unit, sandstones interbedded in the Satanka confining unit in the Laramie Basin locally yield small quantities of water (often mineralized) to wells, commonly with artesian pressure (Littleton, 1950b; Robinson, 1956; Burritt, 1962; Lundy, 1978; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Burritt (1962) speculated that although shales and siltstones in the Satanka confining unit generally were impermeable, secondary porosity and permeability may be present in some areas due to fractures. Most wells completed in the Satanka confining unit are used for stock purposes (Littleton, 1950b; Robinson, 1956; Burritt, 1962). Although not studied in similar detail in other parts of the PtRB, it is likely that Satanka Shale hydrogeologic characteristics are similar to those reported for the Laramie Basin and adjacent Laramie Mountains.

In the Laramie Basin, the Satanka confining unit often is grouped with the overlying Forelle Limestone and Chugwater Formation to collectively describe the hydrogeologic units that confine the underlying Casper aquifer (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Mazor et al., 1993). Collectively, this group of hydrogeologic units that confine the underlying Casper aquifer were informally named the "Permo-Triassic redbeds" by Huntoon and Lundy (1979a) or "redbeds groundwater system/confining unit" by Mazor (1990) and Mazor et al. (1993) (**Plates K, U**) because of the distinctive red color (redbeds) common to these units. Well-yield measurements and other hydraulic properties for the Satanka confining unit are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Satanka confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Satanka confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (1,330 mg/L) indicated that the waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; SMCL of 500 mg/L) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Satanka confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (1,330 mg/L)

indicated that the waters were slightly saline (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Satanka confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 11 wells. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram D**). TDS concentrations were variable and indicated that most waters were fresh (91 percent of samples) and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram D**; supplementary data tables). TDS concentrations ranged from 194 to 2,370 mg/L, with a median of 906 mg/L.

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon, (67 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L) and nitrate, (11 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (73 percent), sulfate (64 percent), and fluoride (14 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (64 percent of samples analyzed for the constituent) and TDS (9 percent; WDEQ Class II standards of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.6 Casper aquifer

The physical and chemical characteristics of the Casper aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Casper aquifer consists of saturated and permeable parts of the Permian and Pennsylvanian Casper Formation, and where present, saturated and permeable parts of the underlying Pennsylvanian Fountain Formation (**Plates J, K, M, T, U**). Both formations are present in the subsurface throughout much of the PtRB, but they crop out only along mountain-basin margins (**Plate 1**). In places, the upper part of the Casper Formation is equivalent to the Tensleep Sandstone and the lower part is equivalent to the Amsden Formation (Mallory, 1967). The Casper Formation is composed of thick sandstones interbedded with thin marine carbonates (limestone and dolomite) deposited in shallow marine, beach, and eolian environments (Pederson, 1953; Mallory, 1967; Benniran, 1970; Kirn, 1972; Huntoon, 1976; Lundy, 1978). The upper part of the Casper Formation generally consists of buff, tan, or reddish-brown, fine- to medium-grained, siliceous, well-cemented sandstone (Dobbin, Hoots, et al., 1929; Harshman, 1972; Lowry et al., 1973; Lundy, 1978). Arkosic sandstone beds in the lower part of the Casper Formation may be tongues of the Fountain Formation, which in the Laramie Basin is at its thickest extent in southern Albany County (Mallory, 1967; Lowry et al., 1973). The Casper Formation grades down to interbedded pink, purple, and gray

dolomitic limestone and dolomite and tan to reddish-brown dolomitic sandstone, sandstone, and quartzite (Dobbin, Hoots, et al., 1929; Harshman, 1972; Lowry et al., 1973). Reported Casper Formation thickness varies substantially by location and ranges from about 500 to 1,200 ft (Pederson, 1953; Lowry and Crist, 1967; Mallory, 1967; Benniran, 1970; Kirn, 1972; Lowry et al., 1973; Huntoon, 1976; Lundy, 1978; Libra et al., 1981; Younus, 1992). The Fountain Formation consists of a 0- to 300-ft-thick sequence of reddish sandstone, arkose, and conglomerate, with red to purple arenaceous (sandy texture) shale and fine-grained sandstone near the base (Mallory, 1967; Kirn, 1972; Lundy, 1978). Mallory (1975) defined the Fountain Formation as a fan conglomerate from the ancestral Front Range and southern Pathfinder Uplift.

Depending on location, the Casper aquifer is confined from above by the Goose Egg, Opeche, Satanka, or Phosphoria confining units (**Plates J, K, M, T, U**). The Casper aquifer is underlain by different hydrogeologic units in different areas of the PtRB —the Amsden aquifer in the Granite Mountains Uplift and Shirley Basin areas (**Plate J**); the Madison aquifer, Englewood Limestone, or Fremont Canyon aquifer in the Hartville Uplift and the Laramie Mountains (**Plate K**); the Guernsey aquifer in the Denver-Julesburg Basin (**Plate M**); the Madison aquifer in the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas (**Plate T**); and the Madison aquifer in the Hanna and Laramie Basins (**Plate U**). Along part of the western flank of the Laramie Mountains near the city of Laramie, the Casper aquifer directly overlies igneous and metamorphic rocks comprising the Precambrian basal confining unit (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979).

Along parts of the flanks of the Laramie Mountains, in the Hartville Uplift, and in the Denver-Julesburg Basin, the Casper aquifer is interpreted by previous investigators to be hydraulically connected to other underlying and overlying Paleozoic hydrogeologic units, primarily through extensional fractures along the crests of folds, and thus, part of a regional aquifer system (**Plates K, M**) (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Weston Engineering, 2008). Several investigators identified this aquifer system as the "Paleozoic aquifer system" (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) and this name is retained herein (see last column in **Plates K and M**). In their study of the Paleozoic hydrogeologic units in the Casper Mountain area at the northwestern end of the Laramie Mountains, Stacy (1994) and Stacy and Huntoon (1994) identified the aquifer system as the "Madison aquifer" [see "Hydrogeologic role/unit of Stacy (1994) and Stacy and Huntoon, (1994)" column on **Plate K**]. In his study of Paleozoic hydrogeologic units and associated hydrogeologic units in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of the city of Douglas, Garland (1996) identified the aquifer system as the "Casper aquifer" [see "Hydrogeologic role/unit of Garland (1996)" column on **Plate K**].

Sandstone beds with varying primary (intergranular) permeability interbedded with low primary permeability marine carbonates and siltstones commonly comprise the Casper aquifer; the sandstone beds are considered a series of subaquifers confined by the carbonates where unfractured (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Western Water Consultants, Inc., 1995; Garland, 1996). In the Laramie Basin, the upper part of the Casper aquifer may be more permeable than the lower part (Morgan, 1947; Robinson, 1956). In many areas, the confined sandstone subaquifers are hydraulically connected by tectonic features (folds and faults) and associated extensional fracturing (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996). In addition to providing hydraulic connection of interbedded sandstone subaquifers, tectonically induced extensional fractures also can promote secondary permeability development in both the sandstones and carbonates (Davis, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Western Water Consultants, Inc., 1995; Garland, 1996). In fact, permeability of interbedded Casper aquifer limestones is likely negligible without secondary permeability development (Lundy, 1978; Huntoon and Lundy,

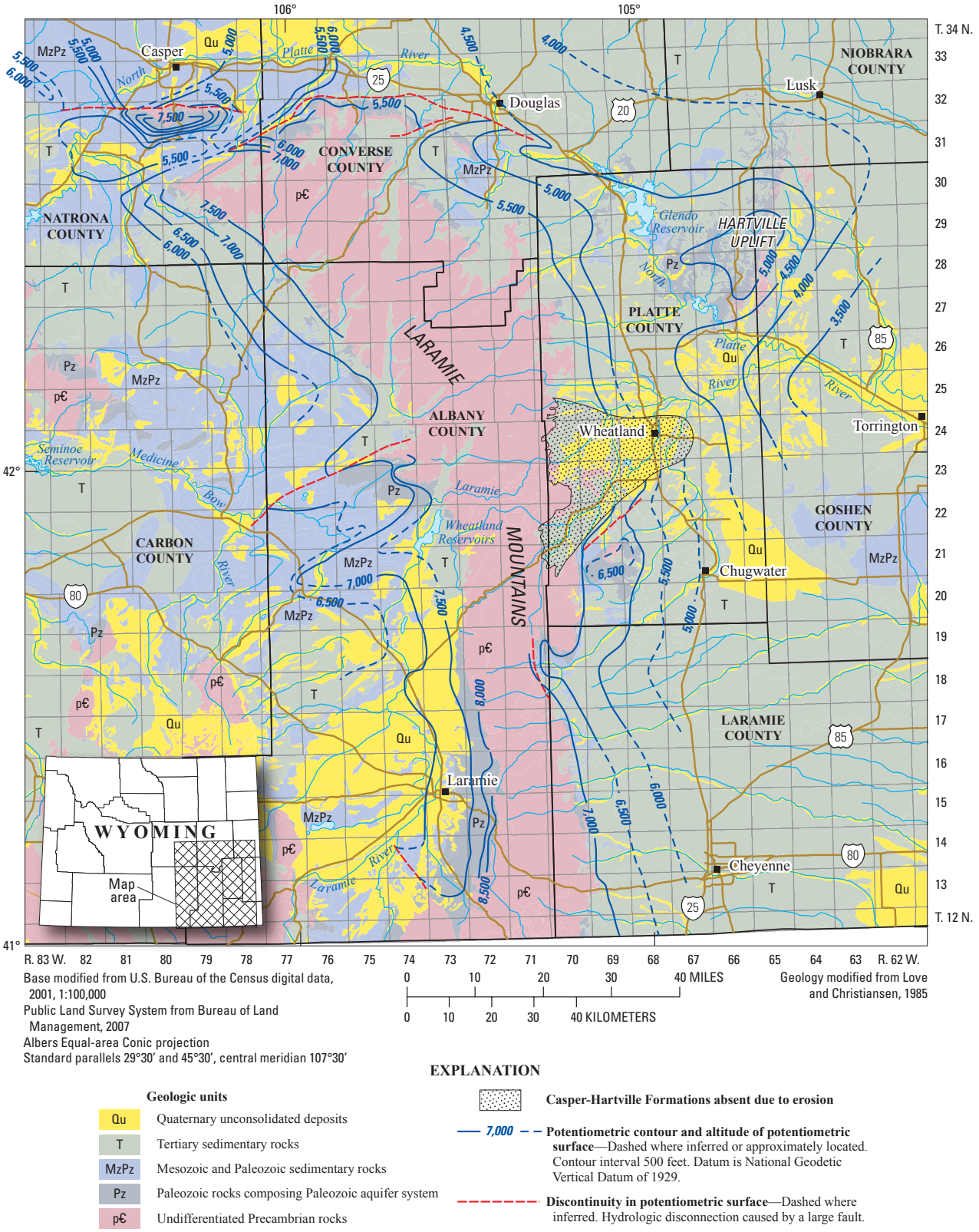


Figure 7-9. Generalized potentiometric surface for the Casper aquifer, southern Laramie Basin, Wyoming (modified from Chen, 1990, Figure 3.5).

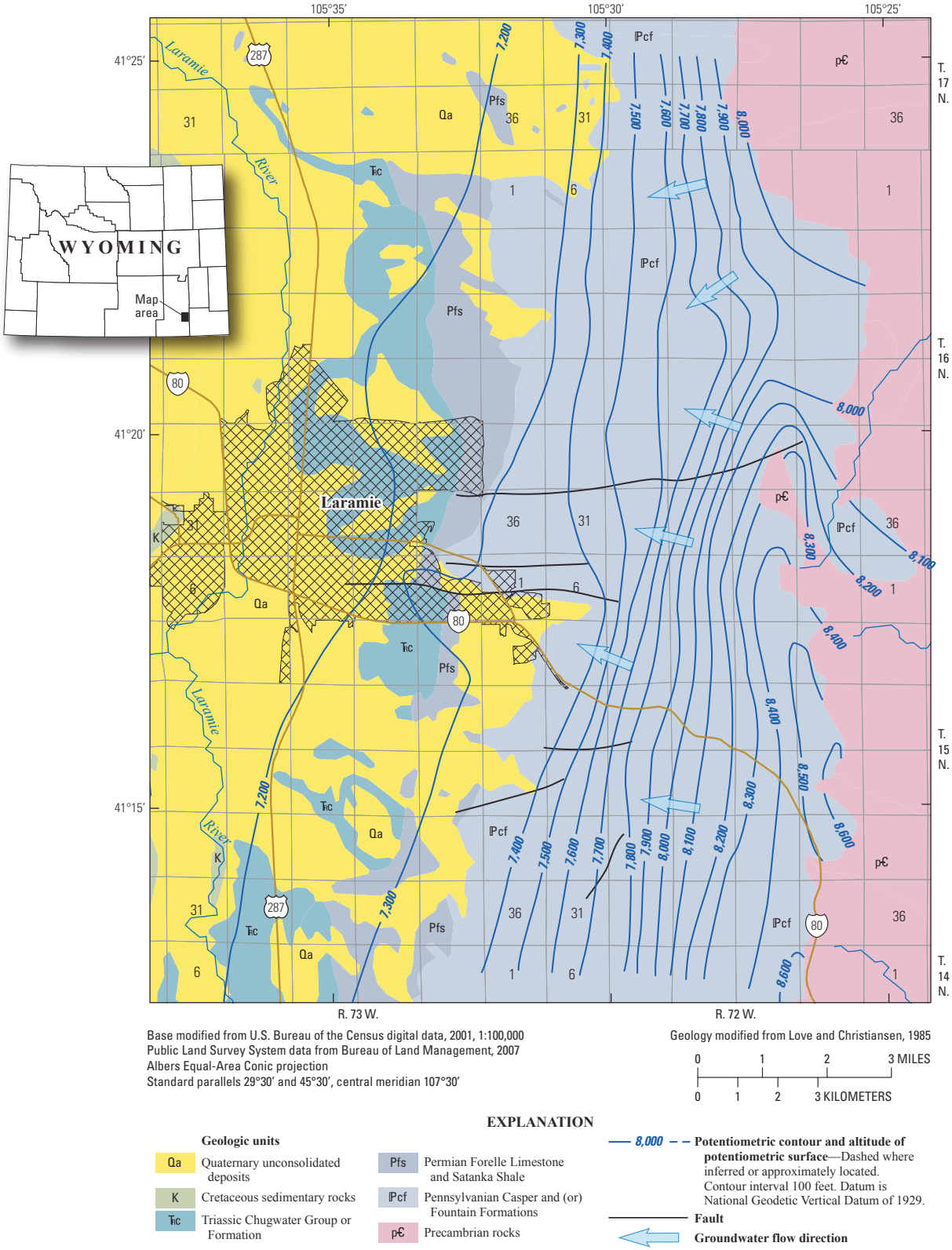


Figure 7-10. Generalized potentiometric surface for the Paleozoic aquifer system in southeastern Wyoming (modified from Western Water Consultants, Inc., 1982, Plate 3).

1979a; Garland, 1996). Joints, bedding-plane partings, and solution enlargement in the carbonate rocks contribute to secondary permeability in the Casper aquifer (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996, and references therein). Karstic development also likely enhances permeability in the Casper aquifer in some areas and also can provide a mechanism for vertical hydraulic connection between different parts of the aquifer or with other Paleozoic hydrogeologic units (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Permeability of Casper aquifer sandstones decreases basinward and with increasing depth in the Laramie Basin, at least partly because of increased cementation of pore space by anhydrite and dolomite and interbedded anhydrite (Garland, 1996). Similarly, Stacy (1994, p. 41) noted that Casper aquifer sandstone intergranular permeability in deeply buried subcrops in the Casper Mountain area "is locally being destroyed through recrystallization and cementation where groundwaters are supersaturated with respect to various minerals."

Vertical fracturing associated with faults can create vertical permeability pathways between the Casper aquifer and through overlying confining units (Lundy, 1978; Mazor, 1990; Mazor et al., 1993; Younus, 1992; Western Water Consultants, Inc., 1994, 1995, and references therein). In such areas, greater hydraulic heads in the Casper aquifer can result in upward circulation of groundwater through the fracture zones; natural mixing between groundwater from the Casper aquifer and overlying hydrogeologic units occurs in the fracture zones (Lundy, 1978; Mazor, 1990; Younus, 1992; Mazor et al., 1993; Western Water Consultants, Inc., 1994). Mixing of groundwater from the Casper aquifer with groundwater from overlying hydrogeologic units also occurs as a result of well-construction practices. In the vicinity of Laramie, wells have been constructed with well screens, perforations, or filter packs penetrating both the Casper aquifer and overlying Permian and Triassic hydrogeologic units (Lundy, 1978; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Some wells are constructed without casing and are open to both the Casper aquifer and overlying Permian and Triassic hydrogeologic units. Consequently, these well-construction methods result in mixing of generally good quality groundwater from the Casper aquifer with generally poorer quality groundwater from overlying hydrogeologic units in the Laramie area (Lundy, 1978; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). In addition, corroded or damaged well casing also may allow for mixing during well pumping (Mazor et al., 1993).

The Casper aquifer is used for stock, domestic, and public-supply purposes (TriHydro Corporation and Lidstone and Associates, Inc., 2007). The Casper aquifer is widely considered to be the only aquifer capable of supplying sufficient quantity and quality of water for public-supply and other uses to the city of Laramie and adjacent areas in the southern Laramie Basin on the western flank of the Laramie Mountains (for example, Western Water Consultants, Inc., 1995, p. 6-1); consequently, the aquifer has been studied extensively in this area (for example, Beckwith, 1937; Boos, 1940; Morgan, 1947; Robinson, 1956; Davis, 1976, 1984; Huntoon, 1976; Banner Associates, 1978; Lundy, 1978; Huntoon and Lundy, 1979a, b, and references therein; Thompson, 1979; Western Water Consultants, Inc., 1982, 1993, 1995; Morrison-Maierle, Inc., 1984a; Younus, 1992; Taboga, 2006; WWC Engineering, 2006a; Wittman Hydro Planning Associates, Inc., 2008). In other parts of the PtRB, Casper aquifer development has been relatively limited; however, exploration of the Casper aquifer and the Paleozoic aquifer system along the flanks of the Laramie Mountains and in the Hartville Uplift continues as the aquifer is considered to have substantial water-supply development potential (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007).

Recharge to the Casper aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, intergranular pores, sinkholes, fractures, and faults (Beckwith, 1937; Lundy, 1978; Peterson, 1991; Younus, 1992; Stacy, 1994; Huntoon and Stacy, 1994; Garland, 1996; Taboga, 2006; Wittman Hydro Planning Associates, Inc., 2008). Recharge to the Casper aquifer on the western flank of the Laramie Mountains in the Laramie area has been estimated by several investigators (Lundy, 1978; Taboga, 2006; Wittman Hydro Planning Associates, Inc., 2008). Lundy (1978) estimated that recharge to the Casper aquifer averaged about 1.4 inches per year (about

8 to 13 percent of average annual precipitation). Using the Soil-Water Balance model (SWB), Wittman Hydro Planning Associates, Inc. (2008, p. 27) estimated recharge to the Casper aquifer averaged about 1 inch per year (about 10 percent of average annual precipitation) for the years 1981 to 2007. The investigators (Wittman Hydro Planning Associates, Inc., 2008, p. 27) also concluded that recharge to the Casper aquifer occurs primarily in late winter and early spring during snowmelt and that the amount and timing of snowpack are crucial to the amount of aquifer recharge; they also noted substantial recharge through faults, averaging about 9 percent of total recharge for the period of study. In the Casper Mountain area on the northwestern end of the Laramie Mountains, Stacy (1994) estimated that recharge to a fault-bound groundwater compartment of the Paleozoic aquifer system (defined as the Madison aquifer and composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) was about 22 percent of average annual precipitation. Garland (1996, Table 1) estimated groundwater recharge to different parts of the Casper aquifer (composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of Douglas to range from 7 to 36 percent of average annual precipitation.

Discharge from the Casper aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams. Major springs that discharge from the Casper aquifer generally are located near faults or steeply dipping folds. High-yielding fault-controlled springs provide a substantial percentage of the water used by the city of Laramie (Beckwith, 1937; Boos, 1940; Morgan, 1947; Robinson, 1956; Davis, 1976, 1984; Lundy, 1978; Huntoon and Lundy, 1979a, b, and references therein; Thompson, 1979; Western Water Consultants, Inc., 1982, 1993, 1995; Younus, 1992; Taboga, 2006; WWC Engineering, 2006a; Wittman Hydro Planning Associates, Inc., 2008). The primary anthropogenic sources of discharge are wells used to supply water (stock, domestic, public supply, and industrial wells) or extract energy resources (oil and gas wells).

Groundwater flow in the Casper aquifer is strongly affected by tectonic structures; fractured and brecciated zones and joints associated with tectonic structures (folds and faults) have substantially increased secondary porosity and permeability (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996; Taboga, 2006). Faults can act as both conduits and barriers to groundwater flow in the aquifer (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996; Taboga, 2006). In the Laramie Basin, high permeability zones in the vicinity of folds and faults "serve as collector structures and conduits for groundwater" and thus, "all major springs and the most productive wells that derive water from the Casper aquifer are located where the aquifer is highly fractured" (Thompson, 1979, p. 16).

Several potentiometric-surface maps have been constructed for parts of the Casper aquifer in the Laramie area (for example, Lundy, 1978; Davis, 1984, Figure 3; Chen, 1990, Figure 3.5; Younus, 1992; Western Water Consultants, Inc., 1995, Plate 6-2; WWC Engineering, 2006a, Plate 10-2). The potentiometric-surface map constructed by Chen (1990, Figure 3.5) is reproduced herein as **Figure 7-9**. All of these potentiometric-surface maps show groundwater flowing from the outcrop area along the western flank of the Laramie Mountains westward towards the interior of the Laramie Basin. In places, high permeability zones associated with tectonic features locally affect groundwater flow and are reflected in potentiometric-surface maps constructed for parts of the Casper aquifer (for example, Lundy, 1978; Western Water Consultants, Inc., 1995, Plate 6-2).

Several potentiometric-surface maps showing groundwater flow in the Paleozoic aquifer system in parts of the PtRB, including the Casper aquifer, have been constructed by previous investigators (Eisen et al., 1980; Libra et al., 1981, Figure IV-1; Western Water Consultants, Inc., 1982, Plate 3; Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in the Denver-Julesburg Basin and Hartville Uplift areas (Eisen et al., 1980; Libra et al., 1981), including the Casper aquifer (composed

of the Casper and (or) Fountain Formations where present), is reproduced herein as **Plate 5**. The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in southeastern Wyoming, including the Casper aquifer where present, is reproduced herein as **Figure 7-10**. These three potentiometric-surface maps show groundwater flowing away from outcrop areas along the flanks of the Laramie Mountains and Hartville Uplift (areas of upland recharge) towards adjacent structural basin interiors.

In parts of the PtRB along mountain-basin margins, thrust faults with substantial vertical displacement sever Casper aquifer and Paleozoic aquifer system hydraulic continuity and thus, disrupt potentiometric-surface continuity (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (for example, see red dashed lines shown on **Figure 7-10**). Severing disrupts hydraulic continuity and segments or compartmentalizes the aquifer or aquifer system into discrete groundwater components or systems; hydraulic connection between the groundwater compartments is limited or absent, and each has a unique groundwater circulation system (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45).

Thompson (1979) constructed a steady-state groundwater-flow model of the Casper aquifer (composed of the Casper and Fountain Formations; **Plate K**) in the Laramie area. Custom-
written by the author using finite-difference techniques, the groundwater-flow model was constructed to predict groundwater-level declines in the Casper aquifer caused by current and anticipated withdrawals in the study area. In addition, the effects of additional groundwater withdrawals on discharge to a fault-controlled spring used to supply water to the city of Laramie (Soldier Springs) were evaluated. After steady-state model development was completed, 17 different alternative groundwater-management scenarios were simulated.

Chemical characteristics

Chemical characteristics of both lithostratigraphic units (Casper and Fountain Formations) comprising the Casper aquifer in the PtRB are described in this section of the report. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

7.4.6.1 Casper aquifer (samples from the Casper Formation)

Sweetwater Arch

The chemical composition of groundwater in the Casper aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (75 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 276 to 1,880 mg/L, with a median of 396 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: gross alpha radioactivity (in the one sample analyzed for this constituent; USEPA MCL of 15 pCi/L), molybdenum (in one of two samples analyzed for this constituent; USEPA HAL of 40 µg/L), radium 226+228 (in the one sample analyzed for this constituent; MCL of 5 pCi/L), and uranium (in the one sample analyzed for this constituent; MCL of 30 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (38 percent; USEPA SMCL of 500 mg/L), iron (33 percent;

SMCL of 300 µg/L; and sulfate (25 percent; SMCL of 250 mg/L; supplementary data tables). Iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class II standard of 15 pCi/L), radium 226+228 (in the one sample analyzed for this constituent; WDEQ Class II standard of 5 pCi/L), and sulfate (25 percent; WDEQ Class II standard of 200 mg/L). Three constituents exceeded State of Wyoming livestock standards: gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class III standard of 15 pCi/L), and radium 226+228 (in the one sample analyzed for this constituent; WDEQ Class III standard of 5 pCi/L), and mercury (in the one uncensored sample analyzed for this constituent; WDEQ Class III standard of 0.05 µg/L). Mercury is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

The chemical composition of groundwater in the Casper aquifer in the SA also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (2,320 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS (WDEQ Class II standard of 2,000 mg/L), chloride (WDEQ Class II standard of 100 mg/L), and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Casper aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were fresh (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 340 to 9,650 mg/L, with a median of 3,060 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (67 percent of samples analyzed for the constituent), chloride (67 percent), fluoride (67 percent; SMCL of 2 mg/L), and sulfate (67 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were TDS (67 percent), chloride (67 percent), sulfate (67 percent), and SAR (50 percent; WDEQ Class II standard of 8). Characteristics or constituents that exceeded State of Wyoming livestock standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

The chemical composition of groundwater in the Casper aquifer in the CBS was characterized

and the quality evaluated on the basis of 55 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram G**). TDS concentrations were variable and indicated that most waters were moderately saline (58 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram G;** supplementary data tables). TDS concentrations ranged from 2,320 to 75,900 mg/L, with a median of 7,630 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (98 percent), chloride (91 percent), and pH (13 percent above upper SMCL limit of 8.5 and 4 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), sulfate (98 percent), and chloride (96 percent). Characteristics and constituents in produced-water samples measured at concentrations at greater than State of Wyoming livestock-use standards were TDS (65 percent), sulfate (40 percent; WDEQ Class III standard of 3,000 mg/L), chloride (38 percent), and pH (13 percent above upper WDEQ Class III limit of 8.5 and 4 percent below lower WDEQ Class III limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 38 percent of produced-water samples.

Medicine Bow Mountains

The chemical composition of groundwater in the Casper aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentrations (191 and 256 mg/L) indicated that the waters were fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Casper aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Casper aquifer in the MBM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (4,170 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS, chloride, and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Casper aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 70 wells and 27 springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram E**). TDS concentrations were variable and indicated that most waters were fresh (95 percent of samples), and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram E**; supplementary data tables). TDS concentrations ranged from 102 to 1,520 mg/L, with a median of 214 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (67 percent of samples analyzed for the constituent exceeded proposed MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (13 percent), sulfate (8 percent), and pH (3 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. One constituent in environmental water samples was measured at concentrations greater than agricultural-use standards was sulfate (11 percent). Concentrations of one characteristic were measured at greater than State of Wyoming livestock-use standards: pH (3 percent above upper limit).

Central Wyoming basins (north)

The chemical composition of groundwater in the Casper aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E6**. The TDS concentration (2,930 mg/L) indicated that the water was slightly saline (**Appendix E6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and two constituents (fluoride and sulfate) exceeded aesthetic standards for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Casper aquifer in the CBN also was characterized and the quality evaluated on the basis of seven produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were moderately saline (57 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 2,660 to 11,200 mg/L, with a median of 3,310 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded

aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (57 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (71 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (29 percent) and sulfate (29 percent). The State of Wyoming Class IV standard for TDS was exceeded in 14 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Casper aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and six springs. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram I**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E7**; **Appendix G5**, **diagram I**; supplementary data tables). TDS concentrations ranged from 172 to 765 mg/L, with a median of 259 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: arsenic (in two of three samples analyzed for this constituent; MCL of 10 µg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (10 percent) and sulfate (10 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. One constituent in environmental water samples measured at concentrations greater than agricultural-use standards was sulfate (10 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Casper aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (3,680 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS, chloride, and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.6.2 Casper aquifer (samples from the Fountain Formation)

Medicine Bow Mountains

The chemical composition of groundwater in the Casper aquifer (samples from the Fountain Formation) in the MBM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (236 mg/L) indicated that the water was fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer (samples from the Fountain Formation) in the MBM was suitable for most uses. No characteristics

or constituents in the Fountain Formation approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Casper aquifer (samples from the Fountain Formation) in the LM was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (224 mg/L) indicated that the water was fresh (**Appendix E5**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer (samples from the Fountain Formation) in the LM was suitable for most uses, but concentrations of one constituent exceeded health-based standards: radon (exceeded proposed and alternative MCL). No characteristics or constituents in the Casper aquifer (samples from the Fountain Formation) approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.4.7 Hartville aquifer

The physical and chemical characteristics of the Hartville aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Hartville aquifer consists of the Late Mississippian, Pennsylvanian, and Permian Hartville Formation, which is a lithostratigraphic unit present in the Denver-Julesburg Basin and Hartville Uplift areas (**Plates 1** and **2; Plate K**). The Hartville Formation is composed of carbonate rocks (limestone and dolomite), sandstone, shale, siltstone, and breccias; sandstones commonly are cherty and dolomitic (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Rapp et al., 1957; Morris and Babcock, 1960; Hoyt , 1962; Welder and Weeks, 1965; Sando and Sandberg, 1987; Wyoming Groundwater, LLC, 2009). Thickness ranges from 0 to 1,225 ft (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Rapp et al., 1957; Morris and Babcock, 1960; Hoyt, 1962; Welder and Weeks, 1965; Libra et al., 1981; Wyoming Groundwater, LLC, 2009). The Hartville Formation has been divided into many smaller lithostratigraphic units/intervals by different investigators (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Hoyt , 1962; Welder and Weeks, 1965; Mallory, 1967; Sando and Sandberg, 1987).

The Hartville aquifer is confined from above by the Opeche and Goose Egg confining units and underlain by the Guernsey aquifer (**Plate K**). In areas near Glendo, overlying Paleozoic and Mesozoic rocks have been eroded and the Cenozoic (Tertiary) White River aquifer/confining unit directly overlies the Hartville aquifer (Welder and Weeks, 1965; Wyoming Groundwater, LLC, 2009). Many studies (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) consider the Hartville aquifer to be part of the regional Paleozoic aquifer system where hydraulically connected to underlying and overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation; that interpretation was retained herein (**Plate K**).

The Hartville aquifer is used as a source of water for public-supply, stock, domestic, and irrigation purposes. The Hartville aquifer is used most heavily as a source of water in the vicinity of Glendo. The aquifer is used to supply water to the town of Glendo, and also is used to supply water for stock, domestic, and irrigation purposes in the area (Morrison-Maierle, Inc.; 1984b; Hibsman and Associates, 1990; Wyoming Groundwater, LLC, 2009).

Sandstones are the most productive zones within the Hartville aquifer (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Libra et al., 1981; Wyoming Groundwater, LLC, 2009). Most wells are completed in a productive white to yellow, fine- to medium-grained, subangular to subrounded sandstone as much as 100-ft thick or more present near the top of the unit known informally as the "Converse sand" (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen et al., 1980;

Libra et al., 1981; Western Water Consultants, Inc., 1982; Wyoming Groundwater, LLC, 2009). In addition to intergranular permeability, fractures reportedly increase Converse sand permeability in some areas (Wyoming Groundwater, LLC, 2009). Carbonate intervals within the Hartville aquifer generally are not productive or are much less productive than sandstones, but brittle carbonates in areas with secondary porosity and permeability ("interconnected fractures, cavities, and solution-enhanced features") may be productive (Wyoming Groundwater, LLC, 2009, p. 4-8). Intervals with secondary porosity and permeability development may be more common in breccias within the Hartville aquifer (Wyoming Groundwater, LLC, 2009). Wells completed in the Converse sand commonly are artesian (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; Wyoming Groundwater, LLC, 2009). Hydrogeologic data describing the Hartville aquifer in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Hartville aquifer in the Glendo area is from losing streams, overlying hydrogeologic units, and precipitation on outcrops (Welder and Weeks, 1965). Streamflow losses from Spring Creek recharge the Converse sand in some areas in the Glendo area. The North Platte River also provides "considerable recharge" to the Hartville aquifer in some areas in the Glendo area (Welder and Weeks, 1965, p. 29).

Discharge from the Hartville aquifer is both natural and anthropogenic. Natural sources of discharge from the Hartville aquifer in the Glendo area include discharge to the overlying White River aquifer/confining unit and to the alluvium in the North Platte River valley that is now covered by Glendo Reservoir (Welder and Weeks, 1965). In addition, Welder and Weeks (1965, p. 30) noted that discharge from the Hartville aquifer due to "evaporation, transpiration, and springs is probably negligible in the Glendo area." Wyoming Groundwater, LLC (2009, p. 4-9) noted that Buffalo Springs in the Glendo area "represents a local, rather than regional, discharge point" for the Hartville aquifer. Anthropogenic sources of discharge are the various wells completed in the aquifer, many of which are completed in the Converse sand.

Chemical characteristics

The chemical composition of groundwater in the Hartville aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram J**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram J**; supplementary data tables). TDS concentrations ranged from 196 to 472 mg/L, with a median of 286 mg/L.

Concentrations of some characteristics and constituents in water from the Hartville aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of two constituents exceeded aesthetic standards for domestic use: manganese (20 percent) and iron (17 percent; USEPA SMCL of 300 µg/L). Dissolved manganese is not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics. No characteristics or constituents exceeded State of Wyoming agricultural- or livestock-use standards.

The chemical composition of groundwater in the Hartville aquifer in the GP also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F6**. TDS concentrations were variable and indicated that most waters were moderately saline (67 percent of samples) and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix F6**; supplementary data tables). TDS concentrations ranged from 2,900 to 7,600 mg/L, with a median of 4,220 mg/L.

Concentrations of some characteristics and constituents in water from the Hartville aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; SMCL of 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 2,000 mg/L), sulfate (100 percent; WDEQ Class II standard of 200 mg/L), and chloride (67 percent; WDEQ Class II standard of 100 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L).

7.4.8 Tensleep aquifer

The physical and chemical characteristics of the Tensleep aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Tensleep aquifer consists of the saturated and permeable parts of the Middle and Late Pennsylvanian Tensleep Sandstone. Present at or near the land surface around uplifts in the PtRB (**Plate 1**), the Tensleep Sandstone is a white to buff, gray, and pink, fine-to medium-grained sandstone with some thin interbedded tan, white, gray, and pink, finely crystalline, dense limestone and dolomite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Mallory, 1967, 1975). Carbonate beds (limestone and dolomite) commonly compose less than 20 percent of the formation (Mallory, 1967). The Tensleep Sandstone was deposited mostly as dunes, but also was deposited in fluvial, beach, and shallow marine environments (Maughan, 1967; Mallory, 1975). In his description of the formation in Wyoming, Mallory (1967) reported that the Tensleep Sandstone is best exposed in the Wind River and Bighorn Basins where reported thicknesses range from 50 to 350 ft. Berry (1960) reported a maximum thickness of 850 ft in the vicinity of the Rawlins Uplift. Reported thickness in the Wind River Basin (WRB) ranges from 200 to 600 ft (Richter, 1981b, Table IV-1). Welder and McGreevy (1966) reported a maximum thickness of about 800 ft in the Great Divide and Washakie Basins and adjacent areas. The Tensleep Sandstone is a source of oil, natural gas, and hydrogen sulfide in parts of the PtRB (De Bruin, 2002).

Depending on location, the Tensleep aquifer is confined from above by the Phosphoria aquifer and confining unit (Granite Mountains Uplift and Shirley Basin; **Plate J**), Goose Egg aquifer and confining unit (Rawlins Uplift; **Plate S**), or Goose Egg confining unit (Sierra Madre, Medicine Bow Mountains, and Saratoga Valley; **Plate T**). The Tensleep aquifer is underlain by the Amsden aquifer in most areas of the PtRB (**Plates J, S, T**). No regional confining unit separates the Tensleep aquifer from the underlying Amsden aquifer. In the vicinity of the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains, the Tensleep aquifer is underlain by the Madison aquifer (Johnson, 1994; Johnson and Huntoon, 1994).

The aquifer is used primarily as a source of water for domestic and stock purposes from wells located along basin margins where the Tensleep Sandstone crops out or is present at shallow depths. On the basis of well yields in the WRB, the uppermost 200 ft of the aquifer may be the most productive (Richter, 1981b). Confined conditions

likely predominate, but unconfined (water-table) conditions are likely in outcrop areas of the Tensleep aquifer. Hydrogeologic data describing the Tensleep aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Early investigators (for example, Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of the Tensleep aquifer. Berry (1960, p. 15) noted that the Tensleep Sandstone was "known to yield water within" the Rawlins Uplift area. Collentine et al. (1981) defined the Tensleep Sandstone as a "major aquifer" in the Great Divide and Washakie Basins, including the adjacent Rawlins Uplift (**Plate S**). In addition, the investigators combined the aquifer with the aquifers in the underlying Amsden Formation and Madison Limestone into a regional aquifer system defined as the "Paleozoic aquifer system" (**Plate S**). Similarly, Richter (1981a) defined the formation as a "principal aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins and adjacent areas (Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas) (**Plates S, T, U**). Because all or parts of the Casper Formation are considered stratigraphically equivalent to the Tensleep Sandstone, Richter (1981a; **Plate T**) referred to aquifers in both formations as the "Casper-Tensleep aquifer." In the WRB and the Granite Mountains area, Richter (1981b) defined the Tensleep Formation as an aquifer within a Paleozoic aquifer system identified as the "Tensleep aquifer system" (**Plate J**). Johnson (1994) and Johnson and Huntoon (1994) noted that the Tensleep aquifer is in hydraulic connection with the Madison aquifer through extensional fractures and faults in the vicinity of Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains. The USGS defined the formation as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Paleozoic aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The Tensleep aquifer is composed of individual sandstone beds separated (confined) by low permeability beds of limestone and dolomite. Permeability in the Tensleep aquifer is both primary (intergranular) and secondary (fractures) (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994, and references therein). Fractures in these low permeability lithologies can provide hydraulic connection between the water-bearing layers. Much of what is known about the physical characteristics of the Tensleep aquifer in the PtRB and other areas of Wyoming commonly is inferred from detailed studies of Tensleep Sandstone characteristics in the Bighorn Basin (for example, Johnson, 1994; Johnson and Huntoon, 1994). On the basis of work conducted in the Bighorn Basin, porosity and permeability in the Tensleep Sandstone is thought to be primarily intergranular and to depend on the amount and type of primary and secondary cementation and recrystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966; Emmett et al., 1971; Mankiewicz and Steidtmann, 1979). Emmett et al. (1971) noted that highly crossbedded sandstones had lower permeabilities than regular bedded sandstones. Fractures and solution processes (in carbonate-rich zones) enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976; Richter, 1981a). Tensleep aquifer transmissivity decreases basinward (Bredehoeft, 1964). Secondary fracture porosity and permeability is common in folds and faults that deform the aquifer, and these locations, as reported in numerous studies in the Bighorn Basin, have the best potential for groundwater development (Jarvis, 1986; Spencer, 1986); by inference, the same potential likely exists in other parts of Wyoming, including the PtRB. In fact, Whitcomb and Lowry (1968) noted that the most productive wells in the Tensleep aquifer in the WRB are associated with local structures where fracturing has increased permeability, and Richter (1981b) noted that permeability in highly fractured parts of the aquifer along the Wind River Mountains might be several orders of magnitude greater than permeability in relatively undeformed areas such as the central part of the WRB.

Permeability of the Tensleep aquifer was examined in greater detail in part of the PtRB by Johnson (1994) and Johnson and Huntoon (1994). The investigators studied permeability of the aquifer in in the vicinity of Troublesome-Difficulty

Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains. As noted previously, the investigators reported permeability to be both intergranular and fracture enhanced. In addition, they noted that movement of water in the aquifer primarily is parallel to bedding, although fractures provide vertical hydraulic connection between permeable units when present. The investigators also noted that in some locations, permeability in the aquifer is enhanced by dissolutional enlargement of fractures and bedding planes.

Recharge to the Tensleep aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, fractures, intergranular pores, sinkholes, fractures, and faults (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). In addition, underlying aquifers such as the Madison aquifer are hydraulically connected to the Tensleep aquifer through extensional fractures in places and can provide interformational recharge to the Tensleep aquifer (Johnson, 1994; Johnson and Huntoon, 1994). Much of the recharge that enters through Tensleep aquifer outcrops is rejected due to basinward decreases in permeability/transmissivity and (or) hydraulic gradients; this rejected recharge is discharged to springs along the contact of the aquifer and overlying confining unit (Johnson, 1994; Johnson and Huntoon, 1994).

Discharge from the Tensleep aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). Numerous springs reportedly discharge "good quality water" (TDS generally less than 500 mg/L) from the Tensleep aquifer along the flanks of the Freezeout Mountains (Richter, 1981a). The primary anthropogenic sources of discharge are wells used to supply water (primarily stock and domestic) or extract energy resources (oil and gas wells).

Potentiometric-surface maps showing groundwater flow in the Tensleep aquifer have been constructed for parts of the aquifer in the PtRB. Collentine et al. (1981, Figure V-7, p. 71) constructed a generalized potentiometric-surface map for the Tensleep aquifer in the Great Divide Basin and the adjacent Rawlins Uplift. The map shows that groundwater generally flows away from the outcrop areas (and presumed source of recharge) along the flanks of the Great Divide Basin and the Rawlins Uplift. In the vicinity of the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains, Johnson (1994) and Johnson and Huntoon (1994) showed that faults sever the Tensleep aquifer, disrupt hydraulic continuity, and compartmentalize the aquifer into three discrete groundwater systems; the groundwater compartments are hydraulically isolated from one another and each has a unique groundwater system with its own recharge, discharge, and groundwater flow characteristics (Johnson, 1994, Plate 3; Johnson and Huntoon, 1994, Plate 3). Some of these Tensleep aquifer groundwater compartments are inactive because they are completely bounded by normal and reverse faults, and thus, little to no groundwater flows into or out of the inactive groundwater system associated with these compartments (Johnson, 1994; Johnson and Huntoon, 1994).

Chemical characteristics

Groundwater-quality data are presented and described for the Tensleep aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Tensleep aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and 13 springs. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram B**). TDS concentrations

were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (88 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; **Appendix G1**, **diagram B**; supplementary data tables). TDS concentrations ranged from 165 to 2,210 mg/L, with a median of 260 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in three samples analyzed for this constituent, concentrations in two samples exceeded the proposed USEPA MCL of 300 pCi/L, and one of these concentrations exceeded the alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (33 percent; USEPA SMCL of 300 µg/L; supplementary data tables), manganese (33 percent; SMCL of 50 µg/L), TDS (25 percent; SMCL of 500 mg/L), sulfate (25 percent; SMCL of 250 mg/L), and fluoride (7 percent; SMCL of 2 mg/L). Dissolved iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were iron (33 percent of samples analyzed for the constituent; WDEQ Class II standard of 5,000 µg/L; supplementary data tables), sulfate (25 percent; WDEQ Class II standard of 200 mg/L), chloride (7 percent; WDEQ Class II standard of 100 mg/L), and TDS (6 percent; WDEQ Class II standard of 2,000 mg/L). Iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Tensleep aquifer in the SA also was characterized and the quality evaluated on the basis of 12 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, **diagram B**). TDS concentrations were variable and indicated that most waters were slightly saline (83 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F1**; **Appendix H1**, **diagram B;** supplementary data tables). TDS concentrations ranged from 1,060 to 6,250 mg/L, with a median of 1,780 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), chloride (75 percent), and TDS (42 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (17 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (17 percent; WDEQ Class III standard of 3,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Tensleep aquifer in the central Wyoming

basins (south) (CBS) was characterized and the quality evaluated on the basis of two environmental water samples from wells. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentrations (276 and 950 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards in one sample and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents in the one sample analyzed for those constituents exceeded health-based standards: arsenic (MCL of 10 µg/L) and gross alpha radioactivity (MCL of 15 pCi/L). In one sample, one characteristic (TDS) and three constituents (fluoride, iron, and sulfate) exceeded aesthetic standards for domestic use. In one sample, two constituents exceeded the State of Wyoming agricultural-use standards: gross alpha radioactivity (WDEQ Class II standard of 15 pCi/L) and sulfate. One constituent (gross alpha radioactivity; WDEQ Class III standard of 15 pCi/L) exceeded State of Wyoming livestock standards in the one sample analyzed for that constituent.

The chemical composition of groundwater in the Tensleep aquifer in the CBS also was characterized and the quality evaluated on the basis of 20 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram H**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram H;** supplementary data tables). TDS concentrations ranged from 1,300 to 23,300 mg/L, with a median of 7,480 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (95 percent), chloride (85 percent), and pH (6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (95 percent of samples analyzed for the constituent), sulfate (95 percent), and TDS (90 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (75 percent), chloride (40 percent; WDEQ Class III standard of 2,000 mg/L), sulfate (30 percent), and pH (6 percent below lower WDEQ Class III limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 30 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Tensleep aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 54 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram G**). TDS concentrations were variable and indicated that most waters were slightly saline (72 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (**Appendix F5**; **Appendix H3**, **diagram G**;

supplementary data tables). TDS concentrations ranged from 1,030 to 18,400 mg/L, with a median of 2,490 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (94 percent), chloride (85 percent), and pH (4 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (94 percent of samples analyzed for the constituent), sulfate (94 percent), and TDS (78 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (9 percent), sulfate (9 percent), and pH (4 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 2 percent of produced-water samples.

7.4.9 Amsden aquifer

The physical and chemical characteristics of the Amsden aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Middle and Early Pennsylvanian and Late Mississippian Amsden Formation is tentatively identified as an aquifer (Amsden aquifer) (**Plates J, S, T**) in the PtRB. Since little is known about the Amsden aquifer in the PtRB, the descriptions of the unit's hydraulic characteristics are primarily based on those properties observed in the adjacent Wind River Basin (WRB) (Richter, 1981b). In the PtRB, the Amsden Formation is present at or near surface around the uplifts (**Plates 1 and 2**) or is deeply buried. The Amsden aquifer is overlain by the Tensleep or Casper aquifers and underlain by the Madison aquifer in the Granite Mountains Uplift and Shirley Basin (**Plate J**). In the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and Rawlins Uplift areas, the Amsden aquifer is overlain by the Tensleep aquifer and underlain by the Madison aquifer (**Plates S, T**).

The Amsden Formation in the WRB is composed of two stratigraphic sequences—a complex upper sequence of "nonresistant shale, dense dolomite, thin cherty limestone, and thin, resistant, fine-grained sandstone," and the basal Darwin Sandstone Member composed of a "fine- to medium-grained, crossbedded to massive, friable, porous sandstone" (Richter, 1981b, Table IV-1, from Keefer and Van Lieu, 1966). Reported thickness of the Amsden Formation ranges from 0 to 400 ft in the WRB (Richter, 1981b, Table IV-1).

In the rest of the PtRB, the Amsden Formation consists of three members: an upper Ranchester Limestone Member, a middle Horseshoe Shale Member, and a lower Darwin Sandstone Member (Mallory, 1967, 1975; Sando et al., 1975). The Ranchester Limestone Member is a sequence of gray, tan, pink, or purple, dense or finely crystalline, cherty dolomite, dolomitic limestone, and limestone (Mallory, 1967, 1975; Sando et al., 1975). They also described the Ranchester Limestone Member including some interbedded pink to dark-red to green shale or shaly limestone, and white to gray fine-to medium-grained sandstone, siltstone, and claystone. It is a marine deposit that is as much as 280-ft thick in Carbon County (Mallory, 1967, 1975; Sando et al., 1975). According to Mallory (1967, 1975) and Sando et al. (1975), the Horseshoe Shale Member is a red to purple or maroon shale, siltstone, and mudstone that is locally yellowish and light pinkish-gray with some beds and lenses of red fine-grained

commonly calcareous sandstone, and silty, sandy, or argillaceous limestone. Sando et al. (1975) proposed that the Horseshoe Shale Member was deposited in a lagoonal environment. It is as much as 150-ft thick in Carbon County (Mallory, 1967; Sando et al., 1975). The Darwin Sandstone Member is a gray, white, cream, to salmon-colored fine-to medium-grained quartz sandstone with silica and locally calcite cement (Mallory, 1967; Sando et al., 1975). The sandstone was deposited in a complicated network of dunes, beaches, and bars during a dominantly eastward transgressing shoreline following the drowning of a fluvial system that was associated with the karst topography of an eroding Madison Limestone (Mallory, 1967; Sando et al., 1975). Sando and Sandberg (1987, Figure 5) considered the Horseshoe Shale Member of the Amsden Formation in the southern Wind River Mountains to be equivalent to the Darwin Sandstone Member of the Amsden Formation in the Rawlins Uplift and Ferris Mountains areas. The investigators (Sando and Sandberg, 1987, Figure 5) considered the "Darwin Sandstone Member" to be part of the Casper Formation in the northern Laramie Mountains and part of the Hartville Formation in the Hartville Uplift area.

Although tentatively classified as an aquifer herein, relatively little is known about the hydrogeology of the Amsden Formation in the PtRB. In the Rawlins Uplift area, Berry (1960, p. 15), stated that little was known about the water-bearing properties of the Amsden Formation, and that the formation likely "would yield very little water" because of low permeability rocks. Welder and McGreevy (1966) stated that "groundwater possibilities not known, but probably poor" in the Great Divide and Washakie Basins. Similarly, Collentine et al. (1981, Table V-1, p. 46) defined the Amsden Formation as an "aquitard" between the Tensleep aquifer and underlying Madison aquifer in the Great Divide and Washakie Basins and Rawlins Uplift (**Plate S**), and stated that the "unit probably has poor water-bearing potential due to predominance of fine-grained sediments." Saulnier (1968) reported locally permeable zones in the Amsden Formation in the north flank of the Medicine Bow Mountains and Pass Creek Basin areas. Permeability in some parts of the Amsden Formation may be larger than in other parts. In the WRB, permeability in the Darwin Sandstone is present due to joints and partings between bedding planes, and permeability of both the upper and basal sequences may be substantially enhanced where fractured (Richter, 1981b). Richter (1981b, Table IV-1, p. 52) noted that water in the Amsden aquifer in the WRB is confined and that well yields ranged from "between 1 to several hundred gallons per minute." Essentially no development of the aquifer has occurred in the PtRB because higher yields can be obtained from wells completed in other Paleozoic aquifers, often at shallower depth. Consequently, almost no study of the aquifer has occurred and no quantitative hydrogeologic information could be located for the Amsden aquifer in the PtRB.

Chemical characteristics

Groundwater-quality data are presented and described for the Amsden aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix F**).

Sweetwater Arch

The chemical composition of groundwater in the Amsden aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (1,300 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Amsden aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards.

There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively). One constituent (sulfate) exceeded State of Wyoming agricultural-use standards (WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Amsden aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 6,480 to 15,700 mg/L, with a median of 9,450 mg/L.

Concentrations of some characteristics and constituents in water from the Amsden aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent; SMCL of 250 mg/L), and sulfate (100 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent; WDEQ Class II standard of 2,000 mg/L), chloride (100 percent; WDEQ Class II standard of 100 mg/L), and sulfate (100 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (100 percent; WDEQ Class III standard of 5,000 mg/L), chloride (67 percent; WDEQ Class III standard of 2,000 mg/L), and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 33 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Amsden aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (3,540 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Amsden aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.10 Madison aquifer

The physical and chemical characteristics of the Madison aquifer in the PtRB are described in this section of the report.

Physical characteristics

The permeable parts of the Early and Late Mississippian Madison Limestone comprise the Madison aquifer. The Madison Limestone is at or near land surface around most uplifts of the PtRB (**Plate 2**). The Madison Limestone is present in the subsurface throughout much of the PtRB, with the exception of the Denver-Julesburg Basin. Most of the Madison Limestone is pink, purple, and gray limestone, dolomitic limestone and dolomite, with some sandy beds and lenses or beds of greenish-gray to brownish-gray chert (Berry, 1960; Harshman, 1972; Mallory, 1979; Sando and Sandberg, 1987). Units that overlie the Madison Limestone were deposited on well-developed karst topography (Harshman, 1972; Sando et al., 1975). The Madison Limestone is a shallow to moderately deep marine deposit that ranges from 0- to about 500-ft thick (Maughan, 1963; Mallory, 1979). The Madison Limestone has been divided into different members in different parts of the PtRB (for example, Maughan, 1963; Harshman, 1972; Mallory, 1979; Sando and Sandberg, 1987). The Madison Limestone is locally cavernous in outcrop. In the Rawlins area, the basal Madison Limestone is a dark brown or dark reddish-brown arkosic sandstone and conglomerate that grades to a fine-grained red to brown sandstone (Berry, 1960; Maughan, 1963; Harshman, 1972; Mallory, 1979). Sando and Sandberg (1987) suggested that parts of this sandstone may be the Englewood Formation and (or) Fremont Canyon Sandstone. Macke (1993, p. M93) suggested that this actually is the Cambrian-age Flathead Sandstone. This sandstone was deposited in nearshore marine environments around the ancestral Front Range that was an emergent lowland at this time (Mallory, 1979; Sando and Sandberg, 1987).

Depending on location, the Madison aquifer is overlain by the Amsden aquifer in the Granite Mountains Uplift and Shirley Basin (**Plate J**), Rawlins Uplift (**Plate S**), and the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley (**Plate T**). The Madison aquifer is overlain by the Casper aquifer in the Hartville Uplift and Laramie Mountains (**Plate K**) and Hanna and Laramie Basins (**Plate U**). No regional confining unit separates the Madison aquifer from the overlying Amsden and Casper aquifers. The Madison aquifer is underlain by different hydrogeologic units in different areas of the PtRB —the Gallatin confining unit in the Granite Mountains Uplift and Shirley Basin areas (**Plate J**); the Englewood Limestone in the Hartville Uplift and the Laramie Mountains (**Plate K**); the Flathead aquifer in the Rawlins Uplift (**Plate S**); the Precambrian basal confining unit in the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas (**Plate T**); and the Fremont Canyon Sandstone/aquifer in the Hanna and Laramie Basins (**Plate U**).

The Madison Limestone is considered an aquifer by most investigators throughout most of PtRB (**Plates J, K, T, U**). Collentine et al. (1981) defined the Madison Limestone as a "major aquifer" in the Great Divide and Washakie Basins. In addition, the investigator combined the aquifer with aquifers in the overlying Amsden Formation and Tensleep Sandstone and underlying undifferentiated Cambrian rocks into a regional aquifer system defined as the "Paleozoic aquifer system." In contrast, Richter (1981a) did not define the formation as an aquifer in the general vicinity of the Laramie, Shirley, and Hanna Basins. Detailed studies of the Madison Limestone in the vicinity of fault-severed basin-mountain margins in parts of the PtRB all classified the formation as an aquifer (Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). The USGS defined the Madison Limestone as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Paleozoic aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Porosity and permeability in the Madison aquifer is primarily secondary, well-developed in places, and is attributed to solution-enhanced fractures, joints, bedding planes, and caverns (Berry, 1960; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Boner et al., 1976; Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Primary permeability is very low to nonexistent because of the dense and finely crystalline structure of the carbonates composing the aquifer (Boner et al., 1976; Richter, 1981a; Johnson, 1994;

Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Without development of secondary permeability, well yields in the Madison aquifer are likely to be relatively small (Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). The most productive (permeable) parts of the Madison aquifer are in areas with substantial fractures, karstic zones, and cavernous zones in karstic areas (Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Garland (1996) noted that Madison aquifer carbonates in the vicinity of the southern Powder River Basin were "generally tight" but "possess permeability along bedding-plane partings." Aquifer transmissivity is much higher in the basin-mountain margin than in the respective adjacent structural basin and decreases basinward and with increasing depth (Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996).

Along parts of the flanks of the Laramie Mountains, in the Hartville Uplift, and in the Denver-Julesburg Basin, the Madison aquifer is interpreted by previous investigators to be hydraulically connected to other underlying and overlying Paleozoic hydrogeologic units, primarily through extensional fractures along the crests of folds, and thus, part of a regional aquifer system (**Plates K, M**) (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Weston Engineering, 2008). Several investigators identified this aquifer system as the "Paleozoic aquifer system" (Eisen et al., 1980; Western Water Consultants, Inc., 1982) and this name is retained herein (see last column in **Plates K and M**). In their study of the Paleozoic hydrogeologic units in the Casper Mountain area at the northwestern end of the Laramie Mountains, Stacy (1994) and Stacy and Huntoon (1994) identified the aquifer system as the "Madison aquifer" [see "Hydrogeologic role/unit of Stacy (1994) and Stacy and Huntoon, (1994)" column on **Plate K**]. In his study of Paleozoic hydrogeologic units and associated hydrogeologic units in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of the city of Douglas, Garland (1996) identified the aquifer system as the "Casper aquifer" [see "Hydrogeologic role/unit of Garland (1996)" column on **Plate K**].

Several potentiometric-surface maps showing groundwater flow in the Paleozoic aquifer system in parts of the PtRB, including the Madison aquifer, have been constructed by previous investigators (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in southeastern Wyoming, including the Madison aquifer where present, is reproduced herein as **Figure 7-10** and generally shows groundwater flowing away from outcrop areas along the flanks of the mountains (areas of upland recharge) towards adjacent structural basin interiors. In parts of the PtRB along mountain-basin margins, thrust faults with substantial vertical displacement sever Madison aquifer and Paleozoic aquifer system hydraulic continuity and thus, disrupt potentiometric-surface continuity (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (for example, red dashed lines shown on **Figure 7-10**). Severing disrupts hydraulic continuity and segments or compartmentalizes the aquifer or aquifer system into discrete groundwater components or systems; limited to no hydraulic connection exists between the groundwater compartments, and each has a unique groundwater circulation system (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). Isolated groundwater systems commonly develop in both the hanging and footwall blocks (Stacy, 1994; Stacy and Huntoon, 1994).

Although potentially highly productive in places, the Madison aquifer has not been extensively developed in the PtRB. Most wells completed in the Madison aquifer are located along the basin margin where the hydrogeologic unit crops out or is present at relatively shallow depth. Water in the aquifer is generally confined except in the vicinity of outcrops, and some wells may be artesian. Hydrogeologic data describing

the Madison aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Madison aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, fractures, intergranular pores, sinkholes, fractures, and faults (Boner et al., 1976; Collentine et al., 1981; Richter, 1981a, b; Peterson, 1991; Glass and Sultz, 1992; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Recharge from streamflow losses on Madison aquifer outcrops is likely substantial in some areas, as indicated by losses determined using streamflow measurements in the Little Box Elder and Cottonwood Creek areas (Boner et al., 1976; Peterson, 1991; Glass and Sultz, 1992; Garland, 1996). Peterson (1991) indicated that much of the streamflow loss along Little Box Elder Creek was lost to sinkholes in karstic parts of the Madison aquifer. Garland (1996) reported streamflow losses along Sawmill Creek, but he indicated that the amount of water lost cannot be quantified due to alluvium in the area. Garland (1996, Table 1) estimated groundwater recharge ranged from 7 to 36 percent of average annual precipitation to different parts of the Casper aquifer (composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of Douglas.

Discharge from the Madison aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). Garland (1996) estimated that as much as 23 percent of the discharge observed in the Douglas City Spring was derived from recharge from direct infiltration of precipitation and snowmelt on Madison and Casper aquifer outcrops. Much of the recharge that enters through Madison aquifer outcrops may be rejected due to basinward decreases in permeability/transmissivity and (or) hydraulic gradients; this rejected recharge is discharged to springs along the contact of the aquifer and overlying confining unit (Johnson, 1994; Johnson and Huntoon, 1994; Garland, 1996). In addition, groundwater in the Madison aquifer is discharged to topographically low areas where the aquifer crops out or to the land surface in areas where hydraulically connected to the aquifer by vertical extensional fractures (Garland, 1996). The primary anthropogenic sources of discharge are wells used to supply water (stock and domestic) or extract petroleum.

Chemical characteristics

Groundwater-quality data are presented and described for the Madison aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Madison aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentrations (170 and 233 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Madison aquifer in the SA was suitable for most uses, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). No characteristics or constituents in the Madison aquifer approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

The chemical composition of groundwater in the Madison aquifer in the SA also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (1,090 and 1,290 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Madison aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use in both samples (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively). Chloride and sulfate exceeded State of Wyoming agricultural-use standards in both samples (WDEQ Class II standards of 100 mg/L and 200 mg/L, respectively). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Madison aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,140 to 7,070 mg/L, with a median of 2,880 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent; SMCL of 250 mg/L), sulfate (67 percent), and pH (33 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 2,000 mg/L), chloride (100 percent), and sulfate (67 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (33 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Laramie Mountains

The chemical composition of groundwater in the Madison aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and three springs. Summary statistics calculated for available constituents are listed in **Appendix E5**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E5**; supplementary data tables). TDS concentrations ranged from 219 to 257 mg/L, with a median of 231 mg/L. On the basis of the characteristics and constituents analyzed, the

quality of water from the Madison aquifer in the LM was suitable for most uses. No characteristics or constituents in the Madison aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Madison aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from fresh to slightly saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 732 to 5,680 mg/L, with a median of 3,150 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: arsenic (in the one sample analyzed for this constituent; USEPA MCL of 10 µg/L) and fluoride (50 percent; MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (in the one sample analyzed for this constituent; SMCL of 300 µg/L), manganese (in the one sample analyzed for this constituent; SMCL of 50 µg/L), sulfate (100 percent), chloride (83 percent), and fluoride (75 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were manganese (in the one sample analyzed for this constituent; WDEQ Class II standard of 200 µg/L), sulfate (100 percent), TDS (83 percent), chloride (83 percent), SAR (33 percent; WDEQ Class II standard of 8), and boron (25 percent; WDEQ Class II standard of 750 µg/L). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (17 percent) and sulfate (17 percent; WDEQ Class III standard of 3,000 mg/L).

The chemical composition of groundwater in the Madison aquifer in the CBN was characterized and the quality evaluated on the basis of 10 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram H**). TDS concentrations were variable and indicated that most waters were moderately saline (60 percent of samples), and remaining waters were slightly saline (**Appendix F5**; **Appendix H3**, **diagram H;** supplementary data tables). TDS concentrations ranged from 1,220 to 7,770 mg/L, with a median of 3,160 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (90 percent), chloride (70 percent), and pH (38 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent), sulfate (90 percent), and TDS (70 percent). Characteristics

and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (38 percent below lower WDEQ Class III limit of 6.5), TDS (20 percent), and sulfate (20 percent).

Great Plains

The chemical composition of groundwater in the Madison aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were fresh (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 843 to 1,250 mg/L, with a median of 1,160 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: lead (the concentration in one of two samples analyzed for this constituent exceeded the USEPA MCL (action level) of 15 µg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), manganese (100 percent), sulfate (100 percent), aluminum (the concentration in one of two samples analyzed for this constituent exceeded the lower SMCL limit of 50 µg/L and also exceeded the upper SMCL limit of 200 µg/L), fluoride (50 percent), and iron (50 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), manganese (50 percent), and chloride (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.11 Guernsey aquifer

The Guernsey aquifer is composed of the Early Mississippian Guernsey Formation, a lithostratigraphic unit present only in the Denver Julesburg Basin and Hartville Uplift areas (**Plates 1 and 2**). The Guernsey aquifer is overlain by the Hartville aquifer and underlain by the Englewood Formation/Limestone (**Plate K**). Morris and Babcock (1960, Table 1, p. 22) described the Guernsey Formation in Platte County as a 0- to 200-ft or more thick "hard gray moderately cherty coarsely-bedded limestone; thin-bedded slabby very fine-grained hard, brittle, silty, purple to gray dolomite; and hard dolomitic purple shale and siltstone." Rapp et al. (1957) informally split the Guernsey Formation in Goshen County into upper and lower units. The upper unit was described as a 0- to 135-ft or more thick "hard gray moderately cherty coarsely bedded limestone," whereas the unit below is a 0 to 65 ft or more thick "thin-bedded slabby very fine-grained hard, brittle, silty, purple to gray dolomite interbedded with hard dolomitic purple shale and siltstone" with "about 4 ft of pink arkose near the base" (Rapp et al., 1957, unnumbered table, p. 23). Welder and Weeks (1965, Table 1) reported a thickness of 150 to 250 ft for the Guernsey Formation in the Glendo area; the investigators described the unit as a gray, fine- to coarse-grained cherty limestone interbedded with chalky dolomite, with purple to gray, fine-grained, thin-bedded, brittle dolomite in the lower part and an arkose at the base.

Lithostratigraphy of the Guernsey Formation was reinterpreted by Sando and Sandberg (1987). The investigators concluded that the formation name was not valid and that the "Guernsey Formation" was a "superfluous name." The investigators assigned rocks formerly belonging to the basal part of the Guernsey Formation to the newly defined Fremont Canyon Sandstone and Englewood Formation; furthermore, they argued that the rest of the Guernsey Formation should be assigned to the "Big Goose and Little Tongue Members" of the Madison Limestone. Subsequently, the statewide Phanerozoic chart for Wyoming (Love et al., 1993) retained Sando and Sandberg's establishment of the Fremont

Canyon Sandstone and Englewood Formation, but apparently did not accept reassignment of the rest of the rocks formerly assigned to the Guernsey Formation to the "Big Goose and Little Tongue Members" of the Madison Limestone. Consequently, all three lithostratigraphic units currently are recognized in the PtRB (Love et al., 1993).

Deeply buried in most areas, very few wells are installed in the Guernsey Formation and thus, very little information describing physical and chemical characteristics of this unit is available. The few well-yield and spring-discharge measurements available for the Guernsey aquifer are summarized on **Plate 3**. Because of historical and current use of "Guernsey Formation" for at least some of these rocks, convention in this study was to retain previous lithostratigraphic assignments for the few wells or springs with information that could be used to describe Guernsey aquifer characteristics (**Plate 3**), even though there was some potential that these wells were completed in or springs discharged from the Fremont Canyon Sandstone or Englewood Formation. Rapp et al. (1957, unnumbered table, p. 23) reported that Guernsey Formation "groundwater possibilities were not known," and Morris and Babcock (1960, Table 1, p. 22) reported that the unit was "generally deeply buried and groundwater possibilities unknown." Because little information is available, classification of the lithostratigraphic unit as a hydrogeologic unit is presumptive, but speculative classification of the Guernsey Formation as an aquifer by previous investigators (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; WWC Engineering et al., 2007) was retained herein (**Plate K**). These investigators consider the Guernsey Formation to be permeable and classified as an aquifer in areas where structural deformation has resulted in fracturing. Most of these studies (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) also considered the Guernsey aquifer to be part of the Paleozoic aquifer system where hydraulically connected to underlying and overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation; that interpretation also was retained herein (**Plate K**).

7.4.12 Englewood Formation/Limestone

The Early Mississippian Englewood Formation was defined by Sando and Sandberg (1987). Love et al. (1993) referred to the lithostratigraphic unit as the "Englewood Limestone" in their chart summarizing Wyoming Phanerozoic lithostratigraphy, even though the investigators cited Sando and Sandberg (1987) for unit definition. "Englewood Formation" is used in the subsequent description herein. The Englewood Formation consists primarily of poorly resistant "quartz siltstone, very fine- to fine-grained quartz sandstone (quartzarenite), and silty and sandy dolomicrite [finely grained and crystalline micritic dolomite] that weather red, brown, and orange, and platy beds, and thin interbeds and partings of green-weathering silty, sandy clay shale" (Sando and Sandberg, 1987, p. 9). Beds of medium-grained quartz sandstone that in places are conglomeratic and crossbedded also are present in some locations. Formation thickness ranges from about 13 to 45 ft in the northern Laramie Mountains and adjacent areas, including parts of the Hartville Uplift (Sando and Sandberg, 1987). All or parts of the Englewood Formation were assigned to the basal part of the Guernsey Formation in the Glendo and Hartville areas in previous studies (Sando and Sandberg, 1987). No existing information was located describing the physical and chemical hydrogeologic characteristics of the Englewood Formation in the PtRB or elsewhere in Wyoming, so additional description of the lithostratigraphic unit as part of this study was not possible.

7.4.13 Fremont Canyon aquifer

The physical and chemical characteristics of the Fremont Canyon aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Fremont Canyon aquifer consists of saturated and permeable parts of the Late Devonian Fremont Canyon Sandstone (**Plates K, M, U**). The Fremont Canyon Sandstone was defined and described by Sando and Sandberg

(1987), and the brief description of the formation presented herein is from their study. Present in the northern Laramie Mountains and adjacent areas, including parts of the Hartville Uplift, the Fremont Canyon Sandstone ranges from about 6 to 160 ft in thickness where present. Resistant quartzite and cliff-forming friable to indurated quartz sandstone (quartzarenite) composes most of the formation. In the Laramie Mountains, subarkosic quartz sandstone and sandy conglomerate containing granite pebbles are present near the base. Prior to assignment to the newly described Fremont Canyon Sandstone by Sando and Sandberg (1987), these rocks were formerly assigned to the Deadwood Formation and (or) basal Guernsey Formation. In some older and often-cited reports, some of these rocks were considered Cambrian in age and were identified as "quartzite" (for example, Rapp et al., 1957, unnumbered table, p. 23; Morris and Babcock, 1960, Table 1; Welder and Weeks, 1965, Table 1); these rocks are now considered to be part of the Fremont Canyon Sandstone or Englewood Formation.

The Fremont Canyon aquifer is overlain by the Englewood Formation/Limestone in the Hartville Uplift, Laramie Mountains, and Denver-Julesburg Basin (**Plates K, M**), and the Madison aquifer in the Laramie Basin (**Plate U**). The Fremont Canyon aquifer is underlain by the Flathead aquifer or Precambrian basal confining unit (**Plates K, M, U**). Because of potential to be hydraulically connected to overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996), the unit is tentatively assigned to the Paleozoic aquifer system in the Hartville Uplift, Laramie Mountains, and Denver-Julesburg Basin areas (**Plates K, M, U**).

Very little information is available describing the hydrogeology of the Fremont Canyon Sandstone. Hydrogeologic data describing the Fremont Canyon aquifer found in this study were very sparse, but available well-yield and spring-discharge measurements are summarized on **Plate 3**. Assignment of this lithostratigraphic unit to hydrogeologic unit (aquifer or aquifer system) in this study is based on assignment of the unit to the Paleozoic aquifer system along the flanks of the Laramie Mountains and Hartville Uplift in early studies [Eisen et al., 1980; Western Water Consultants, Inc., 1982 (lithostratigraphic unit now known as Fremont Canyon Sandstone is identified as the Deadwood Formation in these studies)] and by observation of physical aquifer characteristics in the Casper Mountain area at the northwestern end of the Laramie Mountains (Stacy, 1994; Stacy and Huntoon, 1994) and the south-central edge of the Powder River Basin near Douglas (Garland, 1996) (**Plates K, M, U**).

Intergranular permeability of sandstones in the aquifer is likely minimal (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Stacy (1994, p. 41) noted that intergranular permeability of deeply buried subcrops of the Fremont Canyon Sandstone is "locally being destroyed through recrystallization and cementation where groundwaters are supersaturated with respect to various minerals." Garland (1996) described intergranular permeability in the well-cemented sandstone of the Fremont Canyon Sandstone as "poor." Joints, bedding-plane partings, and fractures associated with folds and faults likely provide most Fremont Canyon aquifer permeability (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). In fact, Garland (1996, p. 20) noted that "up to 25 feet of fair to good permeability in joints and bedding-plane partings was observed in the basal part of the sandstone." The Fremont Canyon aquifer is likely in hydraulic connection with overlying Paleozoic hydrogeologic units (Casper and Madison aquifers) through extensional fractures in areas of structural deformation, and thus, part of a Paleozoic aquifer system in these areas (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (**Plates K, M, U**).

Chemical characteristics

The chemical composition of groundwater in the Fremont Canyon aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E5**. Although a TDS concentration was not available, the specific conductance analysis indicated that the water was fresh (**Appendix E5**; supplementary

data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Fremont Canyon aquifer in the LM was suitable for most uses. No characteristics or constituents in the Fremont Canyon aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.4.14 Gallatin and Gros Ventre confining units

The Late Cambrian Gallatin Limestone is composed of as much as 450 ft of dense, thinly laminated to massive, glauconitic and oolitic limestone, shale, silty shale, and thin sandstone interbeds (Richter, 1981b, Table IV-1, and references therein). The Middle and Late Cambrian Gros Ventre Formation is composed of as much as 750 ft of limestone, shale, and calcareous shale, with a pebble conglomerate at the base (Richter, 1981b, Table IV-1, and references therein). Both units only are present at land surface and in the subsurface in a small part of the PtRB in the Granite Mountains and southern Wind River Mountains. Both units are relatively impermeable in these areas, so they were classified as confining units by Richter (1981b) and that classification is retained herein (**Plate J**). Where present, both hydrogeologic units confine the underlying Flathead aquifer (**Plate J**). Although classified as regional confining units, parts of the hydrogeologic units may be permeable in areas where joints and fractures are present (Richter, 1981b). Springs discharge small quantities (less than 5 gal/min) of water from the Gallatin confining unit along the Wind River Mountains (Richter, 1981b). No additional information was located describing the physical and chemical hydrogeologic characteristics of the Gallatin and Gros Ventre confining units in the PtRB, so additional description as part of this study was not possible.

7.4.15 Aquifers in undifferentiated Cambrian rocks

The physical and chemical characteristics of aquifers in undifferentiated Cambrian rocks in the PtRB are described in this section of the report.

Physical characteristics

Undifferentiated Cambrian rocks occur in parts of the PtRB, primarily in areas near the Rawlins Uplift, Great Divide Basin, and Granite Mountains. The rocks are described as an upper sequence of red to reddish-brown shale and green glauconitic sandstone, and a lower sequence of medium-grained quartzitic sandstone that is in part cemented by silica and in part conglomeratic (Berry, 1960; Welder and McGreevy, 1966). The upper part seems to correspond to the sandy facies of the Gros Ventre Formation, whereas the lower part seems to correspond to the Flathead Sandstone as reported by Keefer and Van Lieu (1966). The lower sands are a shore and near-shore deposit in front of a transgressive sea, and the upper unit is a shallow marine and non-marine unit (Keefer and Van Lieu, 1966). Berry (1960) reported a thickness range from 0 to 600 ft in the Rawlins Uplift area, but some or all of these rocks are now assigned to the Flathead Sandstone.

Early investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of undifferentiated Cambrian rocks. Collentine et al. (1981) defined the undifferentiated Cambrian rocks as a "major aquifer" and "major water-bearing zone" in the Great Divide and Washakie Basins. In addition, the investigator combined the rocks with the overlying Madison and Tensleep aquifers into a regional aquifer system defined as the "Paleozoic aquifer system." The USGS also defined the Cambrian rocks as a "principal aquifer" (Whitehead, 1996) and referred to the rocks as part of the "Paleozoic aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Few wells are completed in aquifers in undifferentiated Cambrian rocks. Berry (1960, p. 14) reported that sandstones and conglomerates in undifferentiated Cambrian rocks in the Rawlins Uplift area "yield moderate supplies of water to wells." Hydrogeologic data describing aquifers in undifferentiated Cambrian rocks found in this study were very limited, but available well-yield and spring-discharge measurements are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for aquifers in undifferentiated Cambrian rocks in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of aquifers in undifferentiated Cambrian rocks in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (200 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from aquifers in undifferentiated Cambrian rocks in the SA was suitable for most uses. No characteristics or constituents in aquifers in undifferentiated Cambrian rocks approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in aquifers in undifferentiated Cambrian rocks in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (6,680 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the aquifers and undifferentiated Cambrian rocks in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). TDS exceeded State of Wyoming livestock standards (WDEQ Class III standard of 5,000 mg/L).

7.4.16 Flathead aquifer

The physical and chemical characteristics of the Flathead aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Flathead aquifer consists of the Cambrian Flathead Sandstone, a lithostratigraphic unit present throughout much of the PtRB (**Plates 1 and 2**). The Flathead Sandstone consists of pink, reddish-brown, tan and gray, fine-to medium-grained, arkosic and quartzitic sandstone, with some conglomerate and arkose in the lower part (Keefer and Van Lieu, 1966; Libra et al., 1981, Table IV-1, and references therein; Richter, 1981b, Table IV-1, and references therein). Flathead aquifer thickness varies considerably but generally ranges from 50 to 500 ft (Keefer and Van Lieu, 1966; Richter, 1981b, Table IV-1, and references therein). Depending on location in the PtRB, the Flathead aquifer is overlain by the Gallatin and Gros Ventre confining units in the Granite Mountains and Shirley Basin (**Plate J**); Fremont Canyon aquifer in the Hartville Uplift and the Laramie Mountains (**Plate K**); and the Madison aquifer in the Rawlins Uplift (**Plate S**). The Flathead aquifer is underlain delete by nonporous igneous and metamorphic rocks of the Precambrian basement that comprise a basal confining unit to all aquifers and aquifer systems in the PtRB (**Plates J, K, S**).

Reported descriptions of Flathead aquifer permeability varies by investigator and the location examined. In the Wind River Basin (WRB) and Granite Mountains area, Richter (1981b, Table IV-1) reported that porosity and permeability is intergranular, but that secondary permeability is present along partings between bedding planes and as fractures associated with folds and faults; the investigator classified the Flathead Sandstone as a "major aquifer" in the WRB and adjacent Granite Mountains area (**Plate J**). Boner et al. (1976) and Weston Engineering (2008) noted that the Flathead Sandstone in the southern Powder River Basin and northern flank of the Laramie Mountains was well cemented and poorly sorted with little primary permeability. In addition, Weston Engineering (2008, p. II-4) also noted that bedding-plane partings may provide some permeability, silica cement in the formation is not readily dissolved, and that "permeability of the unit is likely to be similar to that of the underlying Precambrian rocks."

Although considered a potentially good source of groundwater for development by some investigators, the aquifer is essentially undeveloped as a source of groundwater because of deep burial throughout most of the PtRB and the availability of groundwater from shallower aquifers. Water in the aquifer is semiconfined to confined and is likely under high artesian pressures in many areas (Richter, 1981b). Recharge to the Flathead aquifer is likely from infiltration of precipitation and streamflow on outcrop areas, and possibly upward movement of water from the underlying Precambrian basal confining unit (Richter, 1981b). Springs discharge from bedding-plane partings in the unit (Whitcomb and Lowry, 1968; Richter, 1981b). Little hydrogeologic information is available describing the Flathead aquifer because relatively few wells are completed in the unit in the PtRB, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Flathead aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Flathead aquifer in the SA was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (99 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Flathead aquifer in the SA was suitable for most uses. No characteristics or constituents in the Flathead aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming Basins (south)

The chemical composition of groundwater in the Flathead aquifer in the CBS was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (3,930 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Flathead aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural-

use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.5 Precambrian basal confining unit

The physical and chemical characteristics of the Precambrian basal confining unit in the PtRB are described in this section of the report.

Physical characteristics

Undifferentiated igneous and metamorphic rocks (including metasedimentary and metavolcanic rocks) of the Precambrian basement act as a basal confining unit for the Flathead aquifer, as well as for all aquifers and aquifer systems in the PtRB (**Plates J, K, M, S, T, U**). Rocks of Precambrian age occur throughout the PtRB and are exposed at land surface as the core rocks of the largest of the uplifts (**Plates 1, 2**). Little is known about Precambrian rocks at depth in the PtRB; however, wells are completed locally for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out—permeability is attributable to weathered, jointed, fractured, or faulted rocks (Berry, 1960; Whitcomb and Lowry, 1968; Lowry et al., 1973; Collentine et al., 1981; Richter, 1981a, b). These investigators also noted that fractures decreased in both size and number at greater depths. Lowry et al. (1973) noted that the shallow permeable zone typically is less than 100-ft deep. Hydrogeologic data describing the Precambrian basal confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Precambrian basal confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Precambrian basal confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and 19 springs. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram C**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; **Appendix G1**, **diagram C**; supplementary data tables). TDS concentrations ranged from 34 to 714 mg/L, with a median of 140 mg/L.

Concentrations of some characteristics and constituents in water from the Precambrian basal confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the USEPA MCL of 15 pCi/L) and radon (in both samples analyzed for this constituent, the concentrations exceeded proposed MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). Concentrations of one characteristic exceeded aesthetic standards for domestic use: TDS (8 percent; USEPA SMCL of 500 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the WDEQ Class II standard of 15 pCi/L), chloride (8 percent of samples analyzed for the constituent; SMCL of 100 mg/L) and sulfate (8 percent; SMCL of 200 mg/L). One constituent exceeded State of Wyoming livestock standards: gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the WDEQ Class III standard of 15 pCi/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Precambrian basal confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (181 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Precambrian basal confining unit in the CBS was suitable for most uses. No characteristics or constituents in the Precambrian basal confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Sierra Madre

The chemical composition of groundwater in the Precambrian basal confining unit in the Sierra Madre (SM) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (186 mg/L) indicated that the water was fresh (**Appendix E3**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Precambrian basal confining unit in the SM was suitable for most uses. Three constituents exceeded health-based standards: arsenic (MCL of 10 µg/L), gross alpha radioactivity, and radon (exceeded proposed and alternative MCL). One constituent (gross alpha radioactivity) exceeded State of Wyoming agriculture- and livestock-use standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Precambrian basal confining unit in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E4**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 55 to 111 mg/L, with a median of 96 mg/L.

Concentrations of few characteristics or constituents in the Precambrian basal confining unit in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards that could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic exceeded aesthetic standards for domestic use and State of Wyoming livestock-use standards: pH (33 percent below lower SMCL and WDEQ Class III limit of 6.5). No characteristics or constituents exceeded State of Wyoming agricultural standards.

Laramie Mountains

The chemical composition of groundwater in the Precambrian basal confining unit in the LM was characterized and the quality evaluated on the basis of environmental water samples from as many as seven wells and eight springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram F**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E5**; **Appendix G3**, **diagram F**; supplementary data tables). TDS concentrations ranged from 45 to 282 mg/L, with a median of 159 mg/L.

Concentrations of few characteristics or constituents in the Precambrian basal confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards that could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent in the one sample analyzed for that constituent exceeded health-based standards: radon (exceeded proposed and alternative MCL). Concentrations of one characteristic exceeded aesthetic standards for domestic use and State of Wyoming livestock-use standards: pH (15 percent below lower limit). No characteristics or constituents exceeded State of Wyoming agricultural standards.

Chapter 8

Groundwater Development and Use and Basin-wide Water Balance

Paul Taucher, Karl Taboga, James Stafford

Several factors must be considered when planning a groundwater development project:

- Is the resource economically accessible utilizing current drilling, well construction, and water delivery technology?
- Is the water quality sufficient to meet the requirements of its intended use in either an untreated form or following cost effective treatment?
- Is the resource legally available? Legal and political considerations such as competing local water rights, aquifer and surface water depletion, and wildlife impacts constrain groundwater availability under the developing concept of sustainability.
- Can the aquifer provide sufficient quantities of water? Quantity pertains to the rate and duration of production that can be reasonably expected from the completed project wells.

Project engineers, scientists, water managers, operations personnel, and end users continuously evaluate these interrelated factors during a project because a substantial deficiency in any one area may render the entire project infeasible.

Groundwater development in the Platte River Basin is further constrained by two regulatory policies. The *2001Modified North Platte Decree,* or Decree, (**Appendix D**) is the settlement reached between the states of Nebraska, Wyoming and Colorado in litigation before the United States Supreme Court. The Decree limits irrigated acreage and irrigation consumptive use in certain portions of the North Platte Basin, requires replacement of groundwater-irrigation depletions in certain areas, and requires various reporting and administration procedures in consideration of the water-supply availability in the three states. The *Cooperative Agreement for Platte River Research* and *Other Efforts Relating to Endangered Species Habitat along the Central Platte River, Nebraska* between the States of Colorado, Wyoming, and Nebraska and the U.S. Department of the Interior (DOI); and the associated *Platte River Recovery Implementation Program* (PRRIP) (**Appendix D**) implement aspects of the U.S. Fish and Wildlife Service's (USFWS) recovery plans for target species related to habitat, including water supply. While the Decree directly restricts certain types of groundwater development in the Platte River Basin, the PRRIP could impact development to the extent that, groundwater is a component of habitat-related streamflows in the Platte River Basin.

To effectively discuss groundwater development and use within a river basin, the term "withdrawal" and the concept of "consumptive use" must be defined and discussed. A groundwater withdrawal is simply the removal of a volume of water from the ground either by pumping or by capturing discharges from flowing wells or from a spring at its source. To some degree, the consumptive use of a water resource diminishes the amount of water available for other uses and effectively removes that water from the water budget of the drainage basin. Consumptive processes include plant and animal growth, evaporation, transpiration, some industrial processes, and injection into geologic units where depth and water quality preclude future withdrawal. Relatively few uses are wholly consumptive or non-consumptive. Most uses are partially consumptive in that some of the used water is lost while the remainder is returned to the system until it flows out of the basin. For instance, a portion of the groundwater used for irrigation is lost to the consumptive processes of evapotranspiration and plant growth while the remainder is delivered back to the basin's water budget as return flows to surface waters, or as recharge to groundwater. Other examples of partially consumptive uses (with the associated wholly consumptive constituent, in parentheses) include livestock watering (animal growth and evaporation), reservoir storage (evapotranspiration) and domestic wastewater treatment and discharge in sewage or septic systems (evapotranspiration). Other uses such as industrial wastewater storage and disposal in evaporation pits, and water injection for enhanced oil and gas production, or for permanent disposal are considered to be fully consumptive. Throughout this study "use" has essentially the same meaning as "withdrawal", and "depletion" has the same meaning as "consumptive use". The preferred terms, in an attempt to minimize confusion, are "withdrawal" and "consumptive use".

This chapter discusses groundwater development, total withdrawals, and consumptive

uses in the Platte River Basin using information compiled from multiple sources:

- Previous water plans for the Platte River Basin (WWC Engineering, Inc., and others, 2007; Trihydro Corporation, and others, 2006a) and associated on-line documents (Wyoming Water Development Office (WWDC), 2007);
- Numerous previous local and regional studies **(Appendix B, Chapter 7)**;
- Groundwater-permit data provided by the Wyoming State Engineer's Office (SEO), the Nebraska Department of Natural Resources (NDNR), and the Colorado Division of Water Resources (CDWR); and
- SEO 2011 *Hydrographers' Annual Report Water Division 1* (State Engineer's Office, 2012a) and *Depletions Report – Water Year 2011* (State Engineer's Office, 2012b) for the North Platte River Basin. (https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/platte-river-basin).

8.1 Information from previous Water Plans

Total groundwater withdrawals, consumptive uses and the methods used to quantify them in the Platte River Basin were described in the existing WWDC Statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007), which compiled and updated information from the Platte River Basin Water Plan (Trihydro Corporation, and others, 2006a), associated technical memoranda, and other on-line publications. Although the 2007 Statewide Water Plan summarized withdrawal and consumptive use information developed in the 2006 Platte River Basin Plan, there were differences in the volumes reported between the two plans and the various technical memoranda. Direct measurements of irrigation uses were not provided in the WWDC Water Plans, but were estimated based on related information that was provided. Estimates of consumptive uses associated with recreational and environmental uses of groundwater resources were not provided in the previous plans or technical memoranda.

8.2 Groundwater withdrawal and consumptive use estimations in this memorandum

In the absence of direct measurements, groundwater withdrawals and consumptive uses must be estimated. While this may appear to be straightforward, in reality, it becomes quite complex because multiple estimations of the same parameter may be made using different methods and assumptions. Still, the methods used must provide reasonably conservative estimations of withdrawals and consumptive uses and be based on rational assumptions. Therefore, withdrawal and consumptive use values are presented, in the tables shown below, in multiple formats and as ranges of probable values. In some cases, very conservative estimations have been provided for comparison and are explained in the text that accompanies the table. See, for example, the range of annual irrigation withdrawal estimates from SEO data made in Rows 2 - 4 of **Table 8-1a**.

Tables 8-1a through 8-1d summarize and compare various groundwater withdrawal and consumptive use estimates from the SEO and previous WWDC water plans and technical memoranda (WWC Engineering, Inc., and others, 2007; Trihydro Corporation, and others, 2006a) for principal SEO listed water right uses.

- Irrigation (**Table 8–1a**),
- Stock watering (**Table 8–1a**),
- Industrial uses (**Table 8–1b**),
- Community and non-community public supply (**Table 8–1c**),
- Rural domestic (**Table 8–1c**), and
- Other diverse uses (**Table 8–1d**) that involve miscellaneous, monitoring, test, multi-use wells, hereinafter, referred to as "minor uses".

Although the values developed for **Tables 8-1a-e and Tables 8-2a-e** are shown in some cases to a precision of 1 ac-ft., they are generally rounded to the nearest 100 ac-ft. in the following discussion. Percentages carried to one decimal place in the tables are rounded to the nearest whole value.

Estimates of total withdrawal and consumptive use volumes for the first five uses listed above are shown in **Tables 8-1a through 8-1c** and are aggregated in **Table 8-1e**. The mid-range value (average of high and low values) for total annual groundwater withdrawal is 227,100 ac-ft and the corresponding mid-range value for annual consumptive use is 138,800 ac-ft **(Table 8-1e)**. Water use categories, amounts, and estimation methods are discussed in more detail later in this chapter. Minor uses are not included in the totals shown in **Table 8-1e**, because they are not addressed in previous water plans and only SEO permitted withdrawal data **(Table 8-1d)** is available for them.

For other uses, potential volumes calculated from SEO allocated well yields are provided for comparison to rational estimates obtained from previous technical memoranda. The large range of estimates for each use shows that the volumes of groundwater actually used constitute a fraction of what has been allocated to permitted water right holders. For example, the total irrigation withdrawal calculated from SEO permitted yields for "likely existing wells" (883,938 ac-feet/yr in **Table 8-1a**) assumes continuous year-round operation of the permitted irrigation wells. Although, the value is clearly an overestimate, it does provide an instructive upper limit of groundwater withdrawals for irrigation. Two estimates for irrigation consumptive uses of groundwater are shown. The first estimate (184,700 - 452,700 ac-ft/yr) uses a modification (WWC Engineering, Inc., and others, 2007) derived from the methodology mandated by the U. S. Supreme Court decision of 2001 (USSC, 2001). Irrigation consumptive uses of groundwater are calculated by subtracting irrigation consumptive uses of surface water (represented by measured streamflow depletions in the North Platte River) from total (surface water and groundwater) irrigation consumptive uses. This approach probably overestimates groundwater consumptive uses because it assumes that changes in observed streamflows are due solely to irrigation withdrawals. The second estimated range (72,603 - 103,131 ac-ft/yr) was obtained from Technical Memorandum 4.3 (Harvey Economics, 2005) based on "use factors" predicted for high and normal demand years within high, medium, and low economic growth scenarios.

Table 8-1a: Estimates of total groundwater withdrawals and consumptive uses for irrigation and stock watering obtained from various sources. Values from Technical Memorandum 4.3 (Harvey Economics, 2005) shown in **Table 8-1a** are used in **Table 8-1e.**

Table 8-1b: Estimates for various classes of industrial groundwater withdrawals and consumptive uses are shown in **Table 8-1b**. Ranges of consumptive uses, shown and aggregated with other uses in **Table 8-1e**, are compiled from previous water plans and technical memoranda. The general lack of agreement may be ascribed, in large part, to the fact that groundwater uses described and quantified in the water plans and those permitted by the SEO are categorized differently.

Table 8-1c: Estimates for municipal and domestic groundwater withdrawals and consumptive uses are shown in **Table 8-1c**. The ranges of consumptive uses, shown and aggregated with other uses in **Table 8-1e**, are compiled from previous water plans and technical memoranda.

Table 8-1d: Only SEO permitted withdrawal information was available for several minor uses - miscellaneous, monitor, test, other, multi-use - not addressed in previous water plans.

Table 8-1e: Total groundwater withdrawal and consumptive use estimates are shown for principal SEO listed uses, all Colorado Division of Water Resources (CDWR) and Nebraska Department of Natural Resources (NDNR) uses, aggregated values from **Tables 8-1a through 8-1c** and totals compiled from other previous water plans and technical memoranda.

The groundwater withdrawal and consumptive use statistics from previous Water Plans (Trihydro Corporation, and others, 2006a, WWC Engineering, Inc., and others, 2007) are compared with the water balance calculations and groundwater recharge estimates developed for this study **(Chapter 6)**. Future groundwater requirement projections (Trihydro Corporation, and others, 2006a, WWC Engineering, Inc., and others, 2007) are also compared with recharge estimates. **Tables 8-2a-e** summarize these interpretive calculations starting with the amount

Table 8-1a. Total groundwater withdrawal and consumptive use estimates: Irrigation and Stock Watering

Use	*Annual withdrawal (ac-ft/yr)*	*Annual Consumptive-Use (ac-ft/yr)*	*Percent Consumptive Use*	*Estimation method/ Data sources/ Notes*
[a] Permitted irrigation wells	2,023,126	no estimate		SEO permitted yields >50gpm through 12/31/03
	2,861,967	no estimate		SEO permitted yields for irrigation wells through 02/14/11. (See Table 8-6)
	883,938	no estimate		SEO permitted yields for likely existing irrigation wells through 02/14/11. (See Table 8-6)
[b,c] Irrigation	434,588 - 1,065,176	184,700 - 452,700	42.5%	Calculated as difference between total irrigation (surface and groundwater) consumptive use (USSC, 2001) and streamflow depletions for normal & high demand years. (See text)
[c] Irrigation	170,830 - 242,660	72,603 - 103,131	42.5%	Groundwater resources meet 11% of aggregate water demand during normal & high demand years.
[a]Permitted Stock wells (SEO, 2012)	119,358	no estimate		Total permitted yield through 02/14/11. (See Table 8-6)
	86,491	no estimate		Permitted yield for likely existing stock wells through 02/14/11. (See Table 8-6)
[c] Stock Watering	6,300	6,300	100.0%	Stock use considered 100% consumptive

[a] Wyoming State Engineer's Office, 2012
[b] WWC Engineering, Inc., and others, 2007
[c] Harvey Economics, 2005

Table 8-1b. Total groundwater withdrawal and consumptive use estimate: Industrial

Use (Reference)	*Annual withdrawal (ac-ft/yr)*	*Annual Consumptive-Use (ac-ft/yr)*	*Percent Consumptive Use*	*Estimation method / Notes*
[a] Permitted Industrial wells	147,602	no estimate		Total permitted yield through 02/14/11. (See Table 8-6)
	23,438	no estimate		Permitted yield for likely existing wells through 02/14/11. (See Table 8-6)
[a] Permitted CBNG wells	4,556	no estimate		Total permitted yield through 02/14/11. (See Table 8-6)
	417	no estimate		Permitted yield for likely existing wells through 02/14/11. (See Table 8-6)
Conventional Oil & Gas Production and Refining	All Industrial uses were assumed to be 100% consumptive	[b] 17,600 - [c] 28,395	100.0%	Groundwater assumed to constitute 75% of total (surface water and groundwater) withdrawals
Mining & Reclamation		[b] 17,500 - [c] 28,158		
Power Generation		[b] 0 - [c] 8,428		
Aggregate / Concrete		[b] 11,200 - [c] 18,138		
Miscellaneous Industrial		[b] 9,300 - c 15,074		
SUBTOTAL		55,600 - 98,193		
WOGCC Conventional Oil & Gas Produced Water (2005-2011)	[d] 2,467	[d] 1,174	47.6%	WOGCC records 47.6% of produced water was re-injected
WOGCC CBNG Produced Water (2005-2011)	no data	no data		

[a] Wyoming State Engineer's Office, 2012
[b] WWC Engineering, Inc., and others, 2007a
[c] TriHydro Corporation, 2005d
[d] Wyoming Oil and Gas Conservation Commission, 2012

of water available for recharge and non-reservoir evapotranspiration after total consumptive (surface water and groundwater) uses and surface water outflow from the Platte River Basin are subtracted from total precipitation (**Table 8-2a**).

Table 8-2a: Precipitation is the ultimate source of groundwater recharge. Average annual precipitation in the Platte River Basin from 1981 to 1210 (http://prism.oregonstate.edu/) was estimated at about 19,677,577 acre-feet (acre-ft) and is

Table 8-1c. Total groundwater withdrawal and consumptive use estimates: Municipal and Domestic

Use (Reference)	*Annual withdrawal (ac-ft/yr)*	*Annual Consumptive-Use (ac-ft/yr)*	*Percent Consumptive Use*	*Estimation method / Notes*
[a] Permitted Municipal and Domestic wells	498,575	no estimate		Total permitted yield through 02/14/11. (See Table 8-6)
	213,903	no estimate		Permitted yield for likely existing wells through 02/14/11. (See Table 8-6)
[b] Municipal / Community	6,643	no estimate		Estimated average water use each catagory
[b] Community Conjunctive	38,090	no estimate		
[b] Non-Community Public	1,367	no estimate		
[b] Rural Domestic	15,841	no estimate		
[b,c] TOTAL	61,941	17,800	28.7%	[b,c] Combined consumptive use
[c] Municipal and Domestic	12,275 - 18,375	6,125 - 9,150	49.9% - 49.8%	25% of total withdrawals & consumptive use based on water demand factors

[a] Wyoming State Engineer's Office, 2012
[b] Lidstone and Associates and Trihydro Corporation, 2005
[c] Harvey Economics, 2005

Table 8-1d. Total groundwater withdrawal and consumptive use estimates: SEO miscellaneous, monitor, test, other, multi-use we

SEO Permitted Use	*[a]Annual withdrawal (ac-ft/yr)*	*Annual consumptive-use (ac-ft/yr)*	*Estimation method / Notes (See Table 8-6)*
Miscellaneous wells	497,356	no estimate	Total permitted yield through 02/14/11
	39,648	no estimate	Permitted yield for likely existing wells through 02/14/11
Monitor wells	1,096	no estimate	Total Permitted Yield through 02/14/11
	130	no estimate	Permitted yield for likely existing wells through 02/14/11
Test wells	25	no estimate	Total Permitted Yield through 02/14/11
	0	no estimate	Permitted yield for likely existing wells through 02/14/11
Other wells	5,250	no estimate	Total Permitted Yield through 02/14/11
	125	no estimate	Permitted yield for likely existing wells through 02/14/11
Multi-use wells	1,040,007	no estimate	Total Permitted Yield through 02/14/11
	240,847	no estimate	Permitted yield for likely existing wells through 02/14/11

[a] Wyoming State Engineer's Office (2012)

roughly equivalent to average annual precipitation from 1961 to 1990 (http://prism.oregonstate.edu/). Average annual outflows of surface water from the Wyoming Platte River Basin drainage basin from 2007 to 2010 (http://water.usgs.gov/) were adjusted downward to account for diversions from the Little Snake River in the Green River Basin and for groundwater added to surface flows. Subtraction of adjusted total average annual surface water outflows, estimated at 811,900 ac-ft, from average annual precipitation indicates that an estimated 18,865,638 ac-ft of precipitation remain in the Platte River Basin for non-consumptive and consumptive uses, evapotranspiration, and groundwater recharge.

In the second part of **Table 8-2a,** groundwater withdrawal and consumptive use statistics from previous Platte River Basin Water Plans (Trihydro Corporation, and others, 2006a, WWC Engineering, Inc., and others, 2007) are provided, and compared to water balance calculations and

Table 8-1e. Total groundwater withdrawal and consumptive use estimates: All uses

Use	*Annual withdrawal (ac-ft/yr)*	*Annual Consumptive-Use (ac-ft/yr)*	*Percent Consumptive Use*	*Estimation method / Notes*
Total permitted yield	[a] 5,175,791	no estimate		Total permitted yield through 02/14/11 (See Table 8-6)
	[a] 1,488,982	no estimate		Permitted yield for likely existing wells through 02/14/11 (See Table 8-6)
Total permitted yield Wyoming, Colorado, Nebraska	[a,b,c] 5,194,291	no estimate		56,614 WSEO permits as of 02/14/11 217 CDWR permits as of 07/28/09 32 NDNR permits as of 11/22/10 (See Tables 8-6, 8-7, 8-8)
Irrigation, Stock, Municipal, Domestic, Industrial	281,579 - 396,002	152,303 - 207,624	54.1% - 52.4%	Totals of estimates from Tables 8-1a, 8-1b and 8-1c (normal & high demand)
[d] *Summary of current groundwater uses*	193,040 - 261,070	124,410 - 153,120	64.4% - 58.7%	Water demand factors (normal & high demand)

[a] *Wyoming State Engineer's Office (2012)*
[b] *Colorado Division of Water Resources (2012)*
[c] *Nebraska Department of Natural Resources (2012)*
[d] *Harvey Economics (2005)*

groundwater recharge estimates developed in Chapter 6 of this study.

Data for the annual withdrawal and consumptive use calculations, shown on **Table 8-2a**, for high and normal demand years was obtained from varying sources:

- Technical Memorandum 4.3 (Harvey Economics, 2005) to the 2006 Platte River Basin Water Plan provided estimates of total surface water and groundwater withdrawal and consumptive use based on "use factors" predicted for high and normal demand years within high, medium, and low economic growth scenarios. Withdrawal and consumptive use values, presented in **Table 8-2a** for high and normal demand years, are the same for the high and medium growth scenarios. Refer to **Table 8-2e** for further clarification.
- The range of values for evaporation from reservoirs, which is wholly consumptive, was obtained from the 2007 Statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) and Technical Memorandum 2.6 (Trihydro Corporation, 2005e).
- The WSGS compiled data for oil and gas produced water injection, which is also wholly consumptive.
- For comparison only, consumptive use was also estimated from SEO 2011 reports (State Engineer's Office, 2012a, 2012b). Except for industrial consumptive use, which was approximately an order of magnitude larger in the estimate from the 2011 Depletions Report (State Engineer's Office, 2012b), the estimates from Technical Memorandum 4.3 (Harvey Economics, 2005) were generally confirmed.

Subtracting the values for total consumptive uses for high and normal demand years from the value for "precipitation remaining in the Platte River Basin" (18,865,638 ac-ft) returns a range of estimates of the amount of water available for recharge and non-reservoir evapotranspiration in the last line of the table.

Table 8-2b: The midrange value of the range of estimates of the amount of water available for recharge and non-reservoir evapotranspiration calculated on **Table 8-2a** is shown on **Table 8-2b**. Two cases are considered for estimated recharge; the first considers total recharge over the entire drainage basin and the second, recharge only to the sedimentary aquifers in the Platte River Basin. As discussed in Chapter 6, because recharge to Precambrian crystalline terrains at the highest elevations within the Platte River Basin is most likely discharged relatively quickly to surface waters, the estimates for recharge to the sedimentary aquifers probably provides the better estimate for the overall water balance, with recharge amounting to approximately 4 to 13 percent of the amount of precipitation available to recharge and non-reservoir evapotranspiration combined.

Actual non-reservoir evapotranspiration is estimated by subtracting the recharge value obtained

Table 8-2a. Platte River Basin water resources mass balance.

[a] Water balance parameters		Volume (ac-ft)		% of Precipitation	
Figure 3-3 Total average annual precipitation [b] (1981 - 2010)		19,677,577		100%	
Platte River System outflows					
[c] North Platte River outflow to NE		495,689		2.5%	
[d] Interstate Canal outflow to NE	+	286,155		1.5%	
[d] Ft Laramie Canal outflow to NE	+	139,955		0.7%	
Total average annual (surface water) outflow	=	921,799		4.7%	
Adjustments to surface water outflow					
[d] Average annual transbasin diversion from Little Snake River (Green River Basin)	=	12,516		--	
[e] Total average (2005 normal & high demand) groundwater withdrawals less consumptive use (addressed below)		88,290		0.4%	
[f] WOGCC conventional oil & gas produced water (2005-2011) less injected water (addressed below)	+	9,054		0.05%	
- Total groundwater added to surface water outflow	=	97,344		0.5%	
Adjusted total average annual surface water outflow		811,939		4.1%	
= 1969-1990 Precipitation remaining in PtRB	=	**18,865,638**		**95.9%**	
Ranges of average annual withdrawals and consumptive use					
Surface water and groundwater		*Normal Demand Year*		*High Demand Year*	
		Total withdrawals	*Consumptive use*	*Total withdrawals*	*Consumptive use*
[e] Irrigation	-	1,553,000	662,000	2,206,000	930,000
[e] Stock watering	-	6,300	6,300	6,300	6,300
[e] Municipal and domestic	-	49,100	24,500	73,500	36,600
[e] Recreational & environmental	-	8,440	4,410	9,370	4,820
Industrial use and evaporation from reservoirs					
[e] Oil refining and production	+	33,600	33,600	33,600	33,600
[f] Conventional oil & gas produced water injected (2005-2011)	+	17,269	8,215	17,269	8,215
[e] Coal and uranium mining	+	300	300	300	300
[e] Power generation	+	25,000	25,000	25,000	25,000
[e] Miscellaneous and other	+	45,300	45,300	45,300	45,300
Total Industrial	=	121,469	112,415	121,469	112,415
Evaporation from reservoirs: [g] Low and [h] high estimates	-	149,338	149,338	213,800	213,800
- TOTAL average annual withdrawals and consumptive use	=	1,887,647	958,963	2,630,439	1,303,935
1981-2010 Precipitation available to recharge, lost to non-reservoir evapotranspiration, and minor uses	=	*17,906,675*		*17,561,703*	
% of precipitation		*91.0%*		*89.2%*	

[a] Fetter , C. W., 2001
[b] PRISM Climate Group, 2012
[c] USGS Water Resources of the United States, 2012
[d] Wyoming State Engineer's Office, 2012
[e] Harvey Economics, 2005
[f] Wyoming Oil and Gas Conservation Commission, 2012
[g] WWC Engineering, Inc., and others, 2007a
[h] Trihydro Corporation, 2005e

in **Section 6.2, Table 6-3** from precipitation remaining in the basin. For comparison, a value for potential evapotranspiration was provided based on the premise that the rate of evapotranspiration exceeds the rate of precipitation by a factor of at least four (Curtis, 2004). Potential evapotranspiration is the amount of water that would evaporate and transpire if there is always a sufficient amount of water available in the soil to meet demand (Sharp, 2007). In fact, actual evapotranspiration is limited to the amount of water available to the processes of evaporation and transpiration. A second estimate of actual evapotranspiration in the Platte River Basin is also presented using a GIS based regression model developed by the USGS (Sanford and Selnick, 2013) from climate and land-cover data.

Table 8-2c summarizes the high and low estimates for total recharge and recharge to only

Table 8-2b. Range of estimated recharge & non-reservoir evapotranspiration total and sedimentary aquifers.

1969 - 1990 Precipitation available to recharge, lost to non-reservoir evapotranspiration, and other minor uses - Average of high- and low-demand years (precipitation - surface water outflows - total water consumed) 17,734,189 ac-feet	Range (ac-ft)	*Percent of precipitation*
Total estimated Platte River Basin recharge (Table 6-3)	1,323,698 - 3,550,173	7.5% - 20.0%
Total non-reservoir evapotranspiration	16,410,491 - 14,184,016	92.5% - 80.0%
Estimated recharge to Sedimentary Aquifers (Table 6-3)	682,006 - 2,324,334	3.8% - 13.1%
Total non-reservoir evapotranspiration	17,052,183 - 15,409,855	96.2% - 86.9%

Comparative estimates

The Wyoming Climate Atlas[a] indicates that, except for the highest elevations in Wyoming, the rate of evaporation exceeds the rate of precipitation by at least a factor of 4. The potential evaporation rate can greatly exceed the actual volume.

For comparison - total average annual precipitation: 19,677,577 x 4 = 78,710,308 ac-feet

Estimation of evapotranspiration in the Platte River Basin using the USGS regression[b] with climate and land-cover data.

Total non-reservoir evapotranspiration 16,944,718 ac-feet

[a] *Curtis, 2004*

[b] *Sanford and Selnick, 2013*

Table 8-2c. Summary of recharge as percentage of water balance statistics

	PtRB recharge case	[2]Total estimated PtRB recharge		[2]Estimated recharge to sedimentary aquifers	
[1] *Water balance statistics*	Volume (ac-feet)	Low 1,323,698	High - 3,550,173	Low 682,006	High - 2,324,334
[3]Average annual PtRB precipitation (1981 - 2010)	19,677,577	6.7%	- 18.0%	3.5%	- 11.8%
[3]Annual precipitation remaining in PtRB after subtracting surface water outflows from basin	18,865,638	7.0%	- 18.8%	3.6%	- 12.3%
Total consumptive use - surface water and groundwater (average of normal and high water demand years)	1,131,449	----	----	----	- ----
[3]Water available to recharge & evapotranspiration (average of normal and high water demand years)	17,734,189	7.5%	- 20.0%	3.8%	- 13.1%

[1]Table 8-2a

[2]Table 8-2b

[3]Calculated from average annual PtRB precipitation for POR 1969 - 1990

sedimentary aquifers as percentages of various water-balance statistics.

As dziscussed previously, the better case for these analyses considers recharge only to the sedimentary aquifers with recharge amounts constituting 3 to 10 percent of total precipitation. When precipitation is adjusted down by the midrange value (1,131,449 ac-feet) for total annual basin consumptive use (**Table 8-2a**), recharge still accounts for only 3 to 11 percent of precipitation, indicating that consumptive uses form a very small portion of total basin precipitation. The estimated range of recharge to sedimentary aquifers constitutes 4 to 13 percent of the water available for recharge and evapotranspiration combined.

Table 8-2d summarizes various average groundwater use statistics from **Tables 8-1a-c** as percentages of recharge to sedimentary aquifers. Irrigation uses constitute 9 to 30 percent, stock watering comprises 0.3 to 1 percent, municipal and domestic uses equal 1 to 2 percent, industrial uses amount to 3 to 11 percent; and total groundwater consumptive use constitutes 6 to 20 percent of recharge.

According to these calculations, the values for average recharge to the sedimentary aquifers are similar in magnitude to total consumptive use of surface water and groundwater are **(Table 8-2c).** Furthermore, even the low estimate of recharge to the sedimentary aquifers (**Table 8-2b**) far exceeds

Table 8-2d. Summary of groundwater use statistics as percentage of recharge

	PtRB recharge case	[1]Total estimated PtRB recharge			[1]Estimated recharge (sedimentary aquifers)		
Groundwater-use statistics	Avg. volume for normal & high demand years (acre-feet)	Low		High	Low		High
		1,323,698	-	3,550,173	682,006	-	2,324,334
[3]Average annual groundwater withdrawals	227,055	17.2%	-	6.4%	33.3%	-	9.8%
[2]Irrigation	206,745	15.6%	-	5.8%	30.3%	-	8.9%
[2]Stock watering	6,300	0.5%	-	0.2%	0.9%	-	0.3%
[2]Municipal & domestic	15,841	1.2%	-	0.4%	2.3%	-	0.7%
[2]Industrial	76,897	5.8%	-	2.2%	11.3%	-	3.3%
[2]TOTAL	305,783	23.1%	-	8.6%	44.8%	-	13.2%
[3]Average annual groundwater consumptive use	138,765	10.5%	-	3.9%	20.3%	-	6.0%

[1]Table 8-2b
[2]Tables 8-1a-c
[3]Table 8-1e

average annual withdrawals and consumptive uses of groundwater, only **(Table 8-2d)**. Estimates of total average annual groundwater use could be substantially higher, and the estimates of recharge substantially lower, without significantly changing these simple comparative results. In addition, a portion of total groundwater withdrawal is saline water produced from oil and gas operations that would not otherwise be generated as a groundwater resource, but only as a byproduct, and therefore should not be considered a reduction of beneficially useable groundwater resources. While this analysis suggests that groundwater resources are underutilized in the Platte River Basin, it does not take into account that the feasibility of groundwater resource development is highly location-specific. This issue is discussed further in **Chapter 9** in relation to the capacity for future groundwater development in the Platte River Basin.

Table 8-2e: It is also useful to evaluate future groundwater requirements relative to recharge. The 2006 Platte River Basin Water Plan (Trihydro Corporation, and others, 2006a; Harvey Economics, 2005) provides use factor-based estimates of total combined annual withdrawals and consumptive uses for agricultural, municipal and rural domestic, industrial, and recreational uses in 2035. The analysis examines normal and maximum demand cases for low, medium, high economic growth scenarios. The 2007 Statewide Water Plan (WWC Engineering, Inc., and others, 2007) also provides 30-year groundwater projections for municipal and domestic use ranging from 8,900 acre-ft for the low and 11,200 acre-ft for the high growth scenarios. Projected future annual groundwater requirements for the 30-year time-frame are compared to the **Chapter 6** recharge calculations in **Table 8-2e.**

Overall groundwater demands projected for 2035 range from 7 percent of recharge for low growth / normal demand, to 40 percent for high growth / high demand conditions. Thus it appears that estimated recharge volumes are adequate to meet not only current withdrawals **(Table 8-2d)** but perhaps future groundwater demands, as well. However, these analyses do not consider the legal constraints imposed by the North Platte Decree and the PRRIP that may substantially limit groundwater development in the future. The potential for overutilization of groundwater resources is location-specific, both hydrologically and legally, and must be evaluated during the planning stage of any development project. Evaluating potential groundwater resources of the Platte River Basin outside of existing environmental regulations and legal restrictions is beyond the scope of this study.

The following sections discuss the uses that account for nearly all estimated groundwater withdrawals in the 2006 Platte River Basin Update Water Plan (Trihydro Corporation, and others, 2006a) and the 2007 Statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007).

8.2.1 Irrigation

Direct measurements of groundwater volumes used for irrigation are not presented in either the 2006 Platte River Basin final report (Trihydro Corporation, and others, 2006a) or in the 2007 statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007). Instead,

Table 8-2e. [a] Summary of future groundwater requirements as percentages of recharge

Economic growth scenario	*Low*		*Medium*		*High*	
Water demand scenario	Normal	High	Normal	High	Normal	High
Groundwater demand - 2035 total withdrawals (ac-feet)	170,830	240,760	190,490	261,720	203,200	279,930
Percentage of low-range recharge	24.5%	34.6%	27.3%	37.6%	29.2%	40.2%
Percentage of high-range recharge	7.4%	10.5%	8.3%	11.4%	8.8%	12.2%
Groundwater demand - 2035 consumptive use (ac-feet)	100,900	130,610	118,460	148,770	126,070	158,780
Percentage of low-range recharge	14.5%	18.8%	17.0%	21.4%	18.1%	22.8%
Percentage of high-range recharge	4.4%	5.7%	5.1%	6.5%	5.5%	6.9%

[a] Harvey Economics, 2005

estimates of irrigation uses for combined surface water and groundwater based on water use factors were developed using crop-specific information from 1972 through 2001. From these, total diversions and consumptive uses were generated for six cases formulated from low, medium, high economic growth scenarios within the context of both normal and maximum water demand conditions (Harvey Economics, 2005), for the year 2005. The same procedure was used to predict total irrigation diversions and consumptive uses for the year 2035 (discussed above). The 2006 study then developed estimated proportions of groundwater and surface water that constitute total withdrawals and consumptive use for all evaluated uses. Groundwater withdrawals and consumptive volumes were then back-calculated for all uses; see **Tables 8-1a**, and **8-2d** (Harvey Economics, 2005).

In the Platte River Basin, most irrigation use wells are located along streams where water is obtained at relatively shallow depth from Quaternary alluvial aquifers, and to a lesser extent, from Tertiary bedrock aquifers such as the High Plains Aquifer, which may be located some distance from any major stream. Irrigation uses are partially consumptive due to the processes of plant growth and evapotranspiration; consumptive uses are estimated at 35.4 to 42.6 percent of total withdrawals for irrigation (Wyoming Water Development Office, 2007; Harvey Economics, 2005). Within the Platte River Basin, 4,571 SEO wells, 18 Colorado Division of Water Resources (CDWR) wells, and 24 Nebraska Department of Natural Resources (NDNR) wells have been permitted for irrigation use (**Tables 8-6, 8-7, 8-8)**. Updated data for total permits and permitted yields from the SEO, CDWR, and NDNR is shown in **Tables 8-6 through 8-8**.

8.2.2 Livestock watering

Withdrawals and consumptive uses for livestock watering were estimated in the 2006 Water Plan (Trihydro Corporation, and others, 2006a) at 6,300 ac-ft/yr (**Table 8-2c)** using stock-specific daily water requirements (Harvey Economics, 2005) of 10 gal./day/animal for cattle, and 4 gal./day/animal for sheep. It was assumed that all of the water used for livestock watering is consumptively used groundwater. In the Platte River Basin, 8,912 SEO wells, 14 CDWR wells, and 7 NDNR wells have been permitted for stock watering (**Tables 8-6, 8-7, 8-8)**.

8.2.3 Municipal/community public water systems

Community public water systems supply water year-round to essentially the same population (http://www2.epa.gov/region8-waterops). Technical Memorandum 2.2 (Lidstone and Associates and Trihydro Corporation, 2005) to the 2006 Water Plan (Trihydro Corporation, and others, 2006a) compiled groundwater use information for community public water systems from the WWDC 2002 Water System Survey Report, the USEPA Public Water System database (http://www2.epa.gov/region8-waterops), and directly from water system operators and administrators. For systems that otherwise lacked information, average and peak use volumes were calculated by multiplying per capita values obtained from well documented systems (average use - 226 gallons/capita/day-gpcpd) by the population served. Average annual municipal use of groundwater in the Platte River Basin is summarized by drainage subbasin and for the 49 communities that obtain all or part

(conjunctive use of surface and groundwater sources) of their supply from groundwater in Technical Memorandum 2.2, Table 2.2.15 (Lidstone and Associates and Trihydro Corporation, 2005). The groundwater portion of total conjunctive use, presented in Table 2.2.15, is described for each subbasin in Technical Memorandum 2.2. Community (municipal) groundwater total withdrawals from Table 2.2.15 are summarized in **Tables 8-1c and 8-2d**. Details on community public water systems in each drainage subbasin are provided in Chapter 5 of the 2006 Platte River Basin Water Plan (Trihydro Corporation, and others, 2006a) and Technical Memorandum 2.2 (Lidstone and Associates and Trihydro Corporation, 2005). Consumptive use of combined community and domestic groundwater withdrawals is reported in the 2007 statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) at 36.4 percent of the above total withdrawal estimates. Separate consumptive use numbers are not provided for community groundwater withdrawals alone.

Municipal/community use constitutes a relatively small part of overall groundwater withdrawal in the Platte River Basin **(Table 8-2d)**. Information on which particular aquifers are used for community public supplies is provided later in this chapter **(Sections 8.3.4.3 through 8.3.4.5)**. As of February 14, 2011 the SEO has permitted 457 wells for municipal use in the Platte River Basin (**Table 8-6**).

8.2.4 Non-community public water systems

Domestic water withdrawals include non-community public water systems and rural domestic users. The USEPA (2009) classifies non-community public water systems as either transient or non-transient. Transient systems provide water at gas stations, campgrounds and other facilities that are open at least 60 days per year to serve populations that are continuously and highly variable. Non-transient systems regularly supply water to stable populations of at least 25 persons for at least six months per year (e.g., self-supplied facilities).

Groundwater supplies 97.1 percent of the water used by non-community public water systems within the Platte River Basin. Based on USEPA information from 2005, the 2006 Water Plan (Trihydro Corporation, and others, 2006a; Lidstone and Associates and Trihydro Corporation, 2005) indicated that 79 non-community public water supplies were serving an estimated 16,270 people. Highway rest areas, truck stops, and Camp Guernsey accounted for nearly 80 percent of water used by non-community public water systems. Groundwater domestic water usage from these 79 systems, based on a demand factor of 75 gpcpd, was estimated at approximately 1.22 million gal/day or 1.328 acre-ft/year of groundwater. Non-community domestic groundwater use estimates are summarized in **Tables 8-1c and 8-2d**. Details on domestic uses by non-community public water systems in each drainage subbasin are provided in Chapter 5 of the 2006 Platte River Basin Water Plan (Trihydro Corporation, and others, 2006a) and Technical Memorandum 2.2 (Lidstone and Associates and Trihydro Corporation, 2005). Consumptive uses are reported in the 2007 statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) at 36.4 percent of combined community and domestic groundwater withdrawals.

As with municipal withdrawals, total non-community public use constitutes a relatively small fraction of overall groundwater withdrawal **(Table 8-2d)**. Although non-community public use wells are not listed separately in their groundwater permits database, 15,902 SEO wells, 164 CDWR wells (domestic and household), and 1 NDNR well have been permitted for domestic use in the Platte River Basin (**Tables 8-6, 8-7, 8-8**).

8.2.5 Rural domestic

Rural domestic withdrawals are defined as uses by household that are not supplied by municipal or non-community water systems. Nearly all rural domestic supplies are drawn from groundwater. To estimate rural domestic use, subbasin populations were projected by multiplying average county household size (determined from 2000 U.S. census data) by the number of domestic well permits. Then, an average withdrawal rate of 150 to 300 gpcpd was applied to the estimated population numbers (Lidstone and Associates and Trihydro Corporation, 2005). The per capita use rates were determined using data obtained from municipal water systems in the Platte River Basin. Average rural domestic water usage was estimated at 15,841 acre-ft/yr (**Tables 8-1c and 8-2d**). The South Platte and Pathfinder to Guernsey

subbasins account for 62 percent of this volume. The South Platte subbasin contains approximately 35.6 percent of the estimated rural Platte River Basin population, while the Pathfinder to Guernsey subbasin is inhabited by roughly 26.4 percent of the estimated rural basin population. The consumptive use rate is reported in the 2007 statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) at 36.4 percent of combined community and domestic groundwater withdrawals.

Rural domestic use constitutes a small part of overall groundwater withdrawals in the Platte River Basin **(Tables 8-1c and 8-2d)**. Actual rural domestic withdrawals are much less than the amounts projected from SEO permitted yields because domestic wells are typically used intermittently while the SEO projections assume continuous use. In addition, it is likely that some of the permits are inactive. The mapped distribution of domestic permits in the Platte River Basin (**Figures 8-6 through 8-22**) indicates that most rural domestic wells are completed in the basin's principle aquifers, while a smaller number are completed in the basin's confining units. Rural domestic water usage for each of the Platte River Basin drainage subbasins is further discussed in the 2006 Platte river Basin Water Plan (Trihydro Corporation, and others, 2006a) and Technical Memorandum 2.2 to the 2006 Plan (Lidstone and Associates and Trihydro Corporation, 2005).

8.2.6 Combined municipal and domestic withdrawals and consumptive use

Technical Memorandum 4.3 (Harvey Economics, 2005) to the 2006 Water Plan (Trihydro Corporation, and others, 2006a) contains projections of combined municipal and rural domestic groundwater uses as part of an economic study of future groundwater demands for the Platte River Basin **(Table 8-2e)**. The study projected total surface water and groundwater diversions of 197 and 295 gpcpd, for normal and peak demand years, respectively. Based on user interviews and previous basin studies, it was determined that peak year demand factors would be 50 percent higher than those of normal years. Total municipal and rural domestic withdrawals from groundwater were estimated as 25 percent of total diversions. Based on the difference between municipal diversions and effluent discharge, consumptive use of surface water and groundwater was estimated at approximately 50 percent of withdrawals. In comparison, the 2007 Statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) placed consumptive use at 36.4 percent of total withdrawals **(Table 8-1c)**.

8.2.7 Recreation and environmental

Although water in Wyoming has been developed primarily to provide supplies for irrigation, flood control, and for hydroelectric power generation, recreational uses must also be considered. The majority of recreational water use is associated with surface water bodies, (swimming, fishing, camping, waterfowl hunting and boating) and snow (skiing and snowmobiling); although these pastimes are non-consumptive, they do rely on adequate and consistent water sources. Only a few recreational uses, such as snowmaking at the basin's two alpine ski areas and turf irrigation at its nineteen golf courses are consumptive. The Platte River Basin 2006 Water Plan (Trihydro Corporation, and others, 2006a) did not estimate how much groundwater is used for recreation; however, it does provide a list of all golf courses in the basin, and identifies those that utilize groundwater exclusively or in combination with surface water for turf irrigation.

The Platte River Basin 2006 Water Plan (Trihydro Corporation, and others, 2006a) discusses environmental water uses such as maintaining minimum stream flows and reservoir water levels to protect wildlife habitat and fisheries. Specifically, these include surface water withdrawals required to meet SEO in-stream flow filings, U.S. Forest Service instream bypasses, and voluntary minimum levels for US Bureau of Reclamation reservoirs designed to produce and protect fisheries habitat that have been impacted by historical low flow conditions. Consumption of water for environmental uses is minimal and is due primarily to evaporative loss. Except for groundwater discharges to surface waters, which are undetermined, environmental uses of groundwater are not addressed.

8.2.8 Industrial and mining

The 2006 Platte River Basin Water Plan (Wyoming Water Development Office, 2007;

Trihydro Corporation, and others, 2006b; Trihydro Corporation, 2005d) identified the most important industrial water users and estimated groundwater withdrawals by industrial facilities from 1981 through 2000 (**Table 8-1b**). Industrial applications are the second most prevalent use for groundwater in the Platte River Basin (**Table 8-2d**). Primary industrial consumers of groundwater in the Platte River Basin between 1981 and 2000 include conventional oil and gas exploration, refining, and reclamation; coal and uranium mining and mine reclamation, power generation, aggregate and cement production, and miscellaneous uses. The 2006 Platte River Basin Water Plan assumes that most withdrawals for industrial and mining uses are from groundwater sources.

To quantify industrial water use, the authors of the 2006 Platte River Basin Final Report (Trihydro Corporation, and others, 2006a) evaluated SEO permit information for industrial and miscellaneous uses, conducted follow up interviews and written surveys of permit applicants and collected industrial water use information from SEO Division 1 hydrographers - commissioners (Trihydro Corporation, 2005d). In cases where data was not available, permitted yields, which generally overestimate actual withdrawals, were utilized. The 2006 Water Plan (Trihydro Corporation, and others, 2006a; Trihydro Corporation, 2005d; Trihydro Corporation, 2005i), provides details on industrial groundwater use within each of the seven drainage subbasins of the Platte River Basin. An examination of updated records on the SEO database, for this study, found that as of February 14, 2011, 476 groundwater permits for industrial operations and 110 permits for coal bed natural gas (CBNG) production had been issued in the Platte River Basin **(Table 8-6)**.

Tables 8-1b and 8-2d provide groundwater industrial use volumes from the 2007 statewide Framework Water Plan (WWC Engineering, Inc., and others, 2007) for the same applications, reportedly obtained, in part, from data provided in the 2006 Water Plan (Trihydro Corporation, and others, 2006a; Trihydro Corporation, 2005d; Trihydro Corporation, 2005i). There are, however, substantial differences between the volumes reported in the two studies, both for specific uses and for total industrial use. Furthermore, the 2007 Plan provided far fewer details than the 2006 study in support of the reported volumes. Both the 2006 and 2007 Water Plans assumed that industrial water use is 100 percent consumptive and that groundwater constitutes 75 percent of total water used for industrial purposes in the Platte River Basin.

Technical Memorandum 4.3 (Harvey Economics, 2005) to the 2006 Water Plan for the Platte River Basin provided total annual water diversions and consumptive uses that do not separately quantify industrial uses of groundwater. As discussed previously, the estimates contained within this memorandum are calculated for 2005 and projected for 2035 based on use factors presented for low, medium, high economic growth scenarios during normal and high water demand years. Groundwater was estimated to constitute 11 percent of overall annual diversions in the Platte River Basin.

Discharges of groundwater withdrawn as a byproduct during conventional oil and gas production are not required to be permitted with SEO and were estimated from WOGCC information compiled for this study. Records of produced water injection were also obtained from the WOGCC (**Table 8-1b)**. An average of 2,467 ac-ft of groundwater was generated annually during oil and gas production from 2005 through 2011, and an average of 1,174 ac-ft/yr of produced water was injected over the same time period. In contrast to groundwater withdrawn during conventional oil and gas production, groundwater produced during CBNG operations is regulated by the SEO and WDEQ. Although over 100 permits for CBNG wells have been issued **(CBM - Table 8-6)**, WOGCC records indicate there are no current groundwater withdrawals for CBNG in the Platte River Basin.

Groundwater withdrawn for industrial, fuels, and non-fuels mining applications may be of naturally poor quality and in some cases industrial processes degrade water quality. Most industrial groundwater that is not initially used consumptively is either discharged to the surface (sometimes after treatment) under a WYPDES permit issued by WDEQ, injected for permanent disposal, or reused for enhanced oil and gas production. Some industrial wastewater, including water coproduced with oil and gas is evaporated at permitted disposal reservoirs. In some cases industrial wastewater is reused for general industrial purposes such as dust control. Because produced water from oil and gas operations is a byproduct, it probably

would not be withdrawn for any other purpose. Discharged to surface water bodies, produced water increases the overall surface water supply without depleting useable groundwater resources. Injecting produced water for enhanced oil and gas recovery or permanent disposal into aquifers generally too deep to be considered for groundwater development effectively removes water from the system and is, therefore, consumptive. Perhaps produced water injection should not be included on either side of the water balance equation. A good record of industrial discharges under the authority of WYPDES permits was not available for this study.

8.3 Information from hydrogeologic unit studies

In addition to the withdrawal and consumptive use data compiled from previous state water plans, aquifer-specific groundwater use information was compiled from a variety sources for the discussion in **Chapter 7** of hydrogeologic units in the Platte River Basin. **Chapter 7** summarizes the physical, hydrogeologic, and chemical characteristics of the principal hydrogeologic units in the Platte River Basin including the known dynamics of recharge, discharge, and groundwater circulation. Chapter 3 of the 2006 Water Plan (Trihydro Corporation, and others, 2006a) and Technical Memorandum 3.3 (Lidstone and Associates, 2005b) provide similarly tabulated aquifer-specific information based on seven watershed drainage subbasins of the Platte River Basin rather than groundwater subregions.

Appendix B provides a chronological summary of the locations, aquifers, focus, results, and status of groundwater development studies that have been sponsored by the WWDC since 1973 in the Platte River Basin. Many of these studies were used to compile the information presented in **Chapter 7**.

8.4 Groundwater permit information

Groundwater development proceeds primarily by installing water supply wells and, to a lesser degree, by developing natural springs. Permits allowing the appropriation of groundwater are issued and administered by the SEO in Wyoming, the Colorado Division of Water Resources (CDWR) in Colorado, and the Nebraska Department of Natural Resources (NDNR) in Nebraska. For this study, the WSGS acquired groundwater permit data from all three agencies. The SEO provided information for 56,614 groundwater permits through February 4, 2011, including 4,980 newer permits issued between January 1, 2005 and February 2011 **(Tables 8-3, 8-6)**. CDWR provided data for 217 Colorado groundwater permits through July 28, 2009. Data was obtained on 32 Nebraska groundwater permits from the NDNR through November 22, 2010 in the Nebraska part of the Platte River Basin considered in this study **(Table 8-8)**. Limitations and other characteristics of the groundwater-permits databases are described in **Appendix C**. Information for specific SEO groundwater permits can be accessed through the SEO on-line water rights database at: http://seo.state.wy.us/wrdb/PS_WellLocation.aspx. The_database is easy to use and specific information can be queried using various search parameters (e.g., permit number, location, applicant, use).

Groundwater permit information from the CDWR can be accessed at: http://www.dwr.state.co.us/WellPermitSearch/default.aspx.

Information on specific groundwater permits from the NDNR can be accessed at: http://dnrdata.dnr.ne.gov/wellscs/Menu.aspx.

Permits to appropriate groundwater in the Platte River Basin have been mapped for this study and certain data has been tabulated in formats that are highly informative. The maps of permit locations by use contained in **Chapter 8** illustrate the spatial distribution of particular types of groundwater wells throughout the Platte River Basin. Groundwater-permit data is tabulated in this section to summarize the number of permits by:

1) SEO permit status,
2) SEO depth range,
3) SEO yield range,
4) Class of use (SEO, CDWR, NDNR),
5) SEO municipal use, including producing hydrogeologic unit,
6) WDEQ Source Water Assessment Program (SWAP) program.

In addition, permit data are tabulated on maps depicting well locations on **Figures 8-1 through 8-33.** SEO data are tabulated and mapped in this

study for all permits through February 2011 and for permits from 2005 through February 2011 to illustrate development over the last half-decade.

8.4.1 Groundwater permits by permit status

Table 8-3 shows the number of groundwater permits issued by the SEO under the following eight permit-status categories. **Table 8-3** does not include permits from the CDWR or the NDNR.

1. **Fully Adjudicated** – the well has been drilled and inspected, and a certificate of appropriation issued.
2. **Complete** – SEO has received a notice of completion of the well.
3. **Unadjudicated** – the well has not yet been inspected but may have been drilled.
4. **Incomplete** – SEO has not received a notice of completion of the well.
5. **Abandoned** – SEO has received a notice that the well has been physically abandoned.
6. **Expired** – the permit to appropriate groundwater has expired, generally because SEO has not received a notice that the well has been completed within the time period specified in the original permit or extension(s).
7. **Cancelled** – the permit has been cancelled, generally by the original permit applicant; but can be for other reasons.
8. **Undefined** – a permit without a designated status.

Status categories 1, 2, 3, and 5 indicate that permitted wells have been or probably have been drilled; categories 4, 6, and 7 indicate that the wells probably were not completed. For several permits (category 8), status is not included in the database. While **Table 8-3** summarizes only the number of permits issued to develop and use groundwater, permit status can be used to estimate a range of how many wells have actually been drilled in the Platte River Basin by summing status categories 1, 2, 3, and 5 to set a lower limit and including the undefined permits to set an upper limit. Subtracting abandoned permits (category 5) from the range of permits drilled provides a range of likely existing wells in the Platte River Basin. From this analysis, 67 to 77 percent of total permitted wells have actually been installed, 65 to 76 percent of total permits represent likely groundwater production, and 21 to 68 percent of wells permitted since 2005 have been installed, with only 13 recorded well abandonments.

8.4.2 Groundwater permits by depth and yield

Table 8-4 shows the number of permits by depth range, and **Table 8-5** shows the number of

Table 8-3 SEO groundwater permits in the Platte River Basin by permit status.

Permit Status	All Permits Through 2004	New Permits Since 2005
1- Fully Adjudicated	2,586	18
2 - Complete	30,874	994
3 - Unadjudicated	9	33
4 - Incomplete	1,514	1,545
5 - Abandoned	843	13
6 - Expired	84	2
7 - Cancelled	10,177	61
8 - Undefined	5,539	2,314
Total Permits	***51,626***	***4,980***
Probable Wells Drilled	***34,312 - 39,851***	***1,058 - 3,372***
	(66.5 - 77.2%)	***(21.2 - 67.7%)***
Total Likely Existing Wells	***33,469 - 39,008***	***1,045 - 3,359***
	(64.8 - 75.6%)	***(21 - 67.4)***

Table 8-4 SEO groundwater permits in the Platte River Basin by depth.

	All Permits		Cumulative	
Depth Range(feet)	Permits	Percentage	Permits	Percentage
0-50	11836	30.12%	11836	30.12%
51-100	7000	17.81%	18836	47.93%
101-500	18321	46.62%	37157	94.55%
501-1000	1734	4.41%	38891	98.96%
> 1000	409	1.04%	39300	100.00%
Total Permits with Depth information	*39300*	--	--	--
Permits with no Depth information	*17314*	*30.58%*	*56614*	--
Total Permits	*56614 (of Total)*		--	--
	New Permits since 2005		*Cumulative*	
Depth Range(feet)	*Permits*	*Percentage*	*Permits*	*Percentage*
0-50	160	16.28%	160	16.28%
51-100	128	13.02%	288	29.30%
101-500	577	58.70%	865	88.00%
501-1000	107	10.89%	972	98.88%
> 1000	11	1.12%	983	100.00%
Total Permits with Depth information	*983*	--	--	--
Permits with no Depth information	*3997*	*80.26%*	*4980*	--
Total Permits	*4980 (of Total)*		--	--

Table 8-5 SEO groundwater permits in the Platte River Basin by yield.

	All Permits		*Cumulative*	
Yield Range(gpm)	*Permits*	*Percentage*	*Permits*	*Percentage*
0-25	37025	83.65%	37025	83.65%
26-100	1706	3.85%	38731	87.51%
101-500	2154	4.87%	40885	92.37%
501-1000	2151	4.86%	43036	97.23%
> 1000	1225	2.77%	44261	100.00%
Total Permits with Yield information	*44261*	--	--	--
Permits with no Yield information	*12353*	*21.82%*	*56614*	--
Total Permits	*56614 (of Total)*		--	--
	New Permits since 2005		*Cumulative*	
Yield Range(gpm)	*Permits*	*Percentage*	*Permits*	*Percentage*
0-25	4059	92.57%	4059	92.57%
26-100	110	2.51%	4169	95.07%
101-500	116	2.65%	4285	97.72%
501-1000	57	1.30%	4342	99.02%
> 1000	43	0.98%	4385	100.00%
Total Permits with Yield information	*4385*	--	--	--
Permits with no Yield information	*595*	*11.95%*	*4980*	--
Total Permits	*4980 (of Total)*		--	--

permits by yield range. **Tables 8-4** and **8-5** do not include permits from the CDWR or the NDNR.

Approximately 95 percent of all SEO groundwater permits for which depth data are available are for wells less than 500 feet deep, and approximately 48 percent are for wells less than 100 feet deep. From 2005 through February 2011, approximately 88 percent of all SEO groundwater

permits are for wells less than 500 feet deep, and approximately 30 percent are for wells less than 100 feet deep. Many of the permits (80 percent issued after 2005 and 31 percent overall) in the SEO database do not include well depth.

Of the 44,261 groundwater permits in the Platte River Basin database for which yield information is available, approximately 93 and 84 percent are for yields of 0-25 gpm for permits issued after 2005 and for total permits, respectively. Approximately 1 percent of permits issued after 2005 and less than 3 percent of total permits are for yields greater than 1000 gpm. Approximately 5 percent of permits issued after 2005 and 12.5 percent of total permits have been issued for yields greater than 100 gpm. Many of the permits (12 percent issued after 2005 and 22 percent overall) in the SEO database do not include permitted yield.

Permitted depths and yields, and the groundwater-permit locations on **Figures 8-1 through 8-33** illustrate that most wells in the Platte River Basin are planned and completed in near-surface Quaternary and Tertiary hydrogeologic units. This finding confirms that adequate recharge is occurring throughout the Platte River Basin to provide shallow groundwater for a variety of uses.

8.4.3 Groundwater permits by use

Table 8-6 shows the number of SEO groundwater permits issued through February 2011 for nine primary permitted use categories and "other," which includes all other minor or unique uses. Approximately 21 percent of all groundwater permits in the Platte River Basin are for multiple uses. Permit information through July 2009 for Colorado is presented in **Table 8-7;** the list of use categories differs slightly from those in **Table 8-6** for Wyoming. **Table 8-8** shows the number of groundwater permits issued through November 2011 in the Nebraska area of the Platte River Basin for three permitted use categories. Because some permits are issued for multiple uses, the total number of permits by use exceeds the number of permits issued in **Table 8-6**.

Tables 8-6, 8-7, and 8-8 show that most groundwater permits in the Platte River Basin are for domestic use at individual residences, followed by, in decreasing order, monitoring, stock, irrigation, and miscellaneous uses.

Tables 8-9 and 8-10 are expanded summary tables for SEO municipal-use permits, and **Table 8-11** summarizes information on WDEQ SWAP wells and springs that are used for both municipal and non-community public water supply. A brief discussion of the WDEQ SWAP is provided in **Section 8.3.4.5**. The SWAP provides some information beyond what is available in the SEO groundwater-permits data.

8.4.4 Groundwater permits location maps by use

Thirty four maps (**Figures 8-1** through **8-34**) were prepared for this study to illustrate the geospatial distribution of groundwater permits according to use in the Platte River Basin. Only permits for wells that were likely to have been drilled (including abandoned wells) are included on **Figures 8-1** through **8-33.** Groundwater permits are mapped relative to their date of issue (before or after January 1, 2005) on Platte River Basin scale maps and by total well depths on subregion scale figures. Figures have been provided for the following permitted uses:

- Irrigation **(Figures 8-1** through **8-5),**
- Livestock **(Figures 8-6** through **8-13),**
- Municipal **(Figure 8-14),**
- Domestic **(Figures 8-15** through **8-22),**
- SWAP data wells **(Figure 8-23),**
- Industrial **(Figure 8-24),**
- Monitoring **(Figures 8-25** through **8-32),**
- Miscellaneous-use and test wells **(Figure 8-33)**
- Spring locations digitized from USGS topographic maps are shown on **Figure 34**.

The locations of SEO, CDWR, and NDNR permitted wells on **Figures 8-1 through 8-33**, were posted to abridged versions of the surface hydrogeology map prepared for the Platte River Basin (**Plate II**). **Figures 8-1** through **8-33** differentiate groundwater permits issued from January 1, 2005 through February 14, 2011 in order to evaluate how groundwater development in

Table 8-6 SEO groundwater permits in the Platte River Basin by intended use.

Well Type	WSEO Code	Total Number of Permits	New Since 2005	Total Permitted Yield (gpm)	Total Likely Yield* (gpm)
Municipal	MUN	457	19	236,523	57,741
Domestic	DOM	15,902	1,852	262,052	156,162
Industrial	IND	476	12	147,602	23,438
Coalbed Methane	CBM	110	8	4,556	417
Irrigation	IRR	4,571	111	2,861,967	883,983
Stock	STK	8,912	790	119,358	86,491
Miscellaneous	MIS	4,140	508	497,356	39,648
Monitor	MON	9,188	147	1,096	130
Test	TST	678	269	25	0
Other	blank	130	2	5,250	125
Multi-Use	various	12,050	1,262	1,040,007	240,847
Total		***56,614***	***4,980***	***5,175,791***	***1,488,982***

**Includes only wells that are Fully Adjudicated, Complete, and Unadjudicated*

Table 8-7 CDWR groundwater permits in the Platte River Basin by intended use.

Well Type	Total Number of Permits	New Since 2005	Total Permitted Yield (gpm)
Domestic	134	21	1,003
Industrial	3	0	470
Irrigation	18	0	5,966
Stock	14	1	108
Other	14	3	11
Commercial	4	2	17
Household	30	2	144
Total	***217***	***27***	***7,718***

Table 8-8 NDNR groundwater permits in the Platte River Basin by intended use.

Well Type	WSEO Code	Total Number of Permits	New Since 2005	Total Permitted Yield (gpm)
Domestic	DOM	1	1	25
Irrigation	IRR	24	0	10,700
Stock	STK	7	3	57
Total		***32***	***4***	***10,782***

the Platte River Basin has proceeded over that six year period. Substantial groundwater development has occurred in the Platte River Basin since the previous Groundwater Determination (Lidstone and Associates, 2005b). Consistent with the historic trend, it is clear that most permits issued over the 2005 – 2011 period in the Platte River Basin continue to target Quaternary and Tertiary hydrogeologic units.

In order to provide better resolution of location and discrimination of five ranges of well depth in areas where permit density is high, permits for domestic, livestock, and groundwater monitoring were posted to a hydrogeologic base map prepared for each of the seven groundwater areas defined for this study **(Chapter 2)**. Groundwater permits for irrigation were also mapped by both depth and yield in the two groundwater areas with the most irrigation wells:

- Casper Arch, Wind River, and Powder River Basin; and
- Denver Basin and Hartville Uplift.

Matrix tables that correlate range of well depth and permitted yield are also provided on the

groundwater permit maps. Consistent with **Tables 8-4** and **8-5**, the depth vs. yield tables shows that by far the most permits issued in the Platte River Basin are for 0-25 gpm, across all depth ranges. In addition, the insert tables show that fewer wells are permitted for increasingly higher yields across all depth ranges. Because only permits for wells that were likely to have been drilled (status of fully adjudicated, complete, unadjudicated, and abandoned) are included on **Figures 8-1** through **8-33** (not including SWAP wells **Figure 8-23**), the number of permits on the insert matrix tables do not equal the total number of permits by use in **Table 8-6**.

Figure 8-23 shows the distribution of SWAP wells that are used for municipal and other public supply. Because public supply is one of the most important uses of groundwater resources, a more comprehensive compilation was performed for the SEO permit data and related WDEQ SWAP data on municipal and non-community public groundwater supplies.

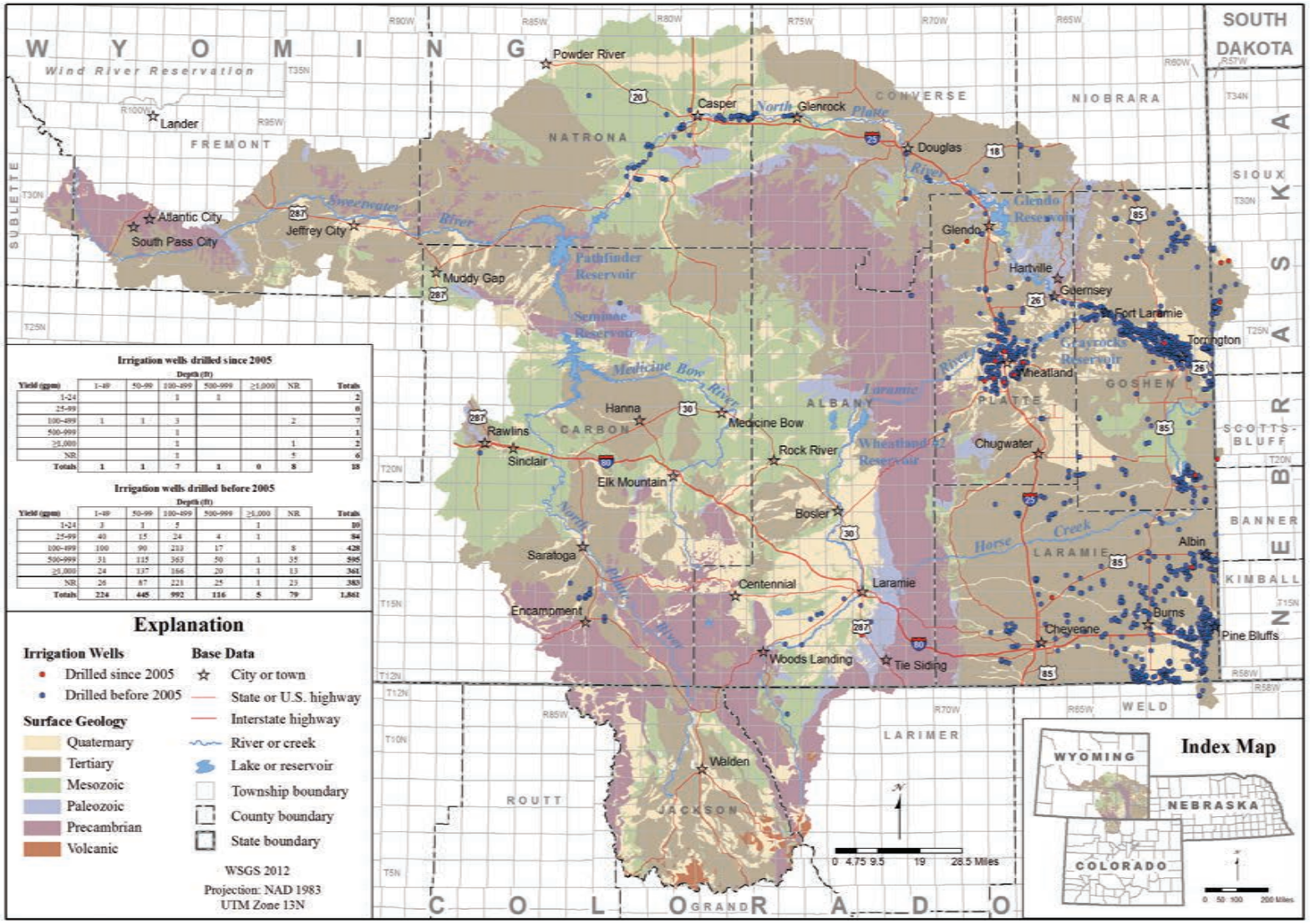
8.4.4.1 Irrigation-use permits

Tables 8-6, 8-7, and 8-8 list 4,613 groundwater permits for irrigation use (IRR) in the greater Platte River Basin with 4,571 in Wyoming, 18 in Colorado, and 24 in Nebraska. **Figure 8-1** shows the distribution of likely drilled irrigation wells in the entire Platte River Basin, issued before and after January 2005. Most irrigation wells are located in rural areas and along rivers and other surface drainages where Quaternary and Tertiary hydrogeologic units provide adequate groundwater for this high-volume use. The depth vs. yield tables on **Figure 8-1** show that while permits have been issued for all depth categories, most groundwater permits are for depths of less than 500 feet, across a wide range of yields for both total permits and permits issued since January 2005. Most wells permitted since 2005 have been for depths of 100 to 500 feet and for yields of 100 to 1000 gpm. A significant number of irrigation-use permits have no recorded depth or yield information. **Tables 8-6, 8-7,** and **8-8** and **Figure 8-1** illustrate that a relatively small fraction of the total number of permits in the Platte River Basin have been issued since 2005, as development is limited in many places by the legal constraints discussed previously in this chapter, in **Chapter 1, and in Appendix D.**

As discussed previously, the two areas in the Platte River Basin with the most irrigation wells are the *Casper Arch, Wind River, and Powder River Basin*; and the *Denver Basin and Hartville Uplift* groundwater sub regions of the Platte River Basin that were defined in **Chapter 2**. **Figures 8-2** through **8-5** illustrate the distribution of irrigation wells over five ranges of depth and permitted yield. Most permits in these two areas appropriate water from wells located near the North Platte River, likely targeting alluvial deposits adjacent to the river. A substantial number of wells in the Denver Basin - Hartville Uplift area are located away from major drainages and directly withdraw water from the High Plains aquifer. Permits for most wells in the High Plains aquifer allow yields ranging from 100 to 499 gpm and were issued prior to 2005.

8.4.4.2 Livestock use permits

Tables 8-6, 8-7, and **8-8** show that 8,912 SEO permits, 14 CDWR permits, and 7 NDNR groundwater permits have been issued for livestock use (STK), a quantity exceeded only by the number of domestic-use and monitoring permits in the Platte River Basin. **Figure 8-6** shows the distribution of likely drilled stock wells in the Platte River Basin issued before and after January 2005. **Figures 8-7** through **8-13** map the distribution of stock wells over five ranges of well depth within the seven subregions of the Platte River Basin specified in **Chapter 2**. Stock wells are located throughout the Platte River Basin, especially in rural areas where groundwater is the sole reliable source of water. The distribution of stock wells shows some higher areas of concentration along rivers and other surface drainages within the interior basins. Although, most stock wells are completed in Quaternary and Tertiary hydrogeologic units, many are completed in outcrops of Cretaceous to Precambrian aquifer and confining units located in areas between larger drainages and along basin uplands. The depth vs. yield tables on **Figure 8-6** show that, by far, the largest number of both total permits and permits issued since 2005 are for depths of 500 feet or less and for yields of



Irrigation wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24			1	1			2
25-99							0
100-499	1	1	3			2	7
500-999			1				1
≥1,000			1			1	2
NR			1			5	6
Totals	**1**	**1**	**7**	**1**	**0**	**8**	**18**

Irrigation wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	3	1	5		1		10
25-99	40	15	24	4	1		84
100-499	100	90	233	17		8	428
500-999	31	115	363	50	1	35	595
≥1,000	24	137	166	20	1	13	361
NR	26	87	221	25	1	23	383
Totals	**224**	**445**	**992**	**116**	**5**	**79**	**1,861**

Figure 8-1. Wyoming SEO, Colorado DWR, and Nebraska DNR permitted and drilled irrigation wells.

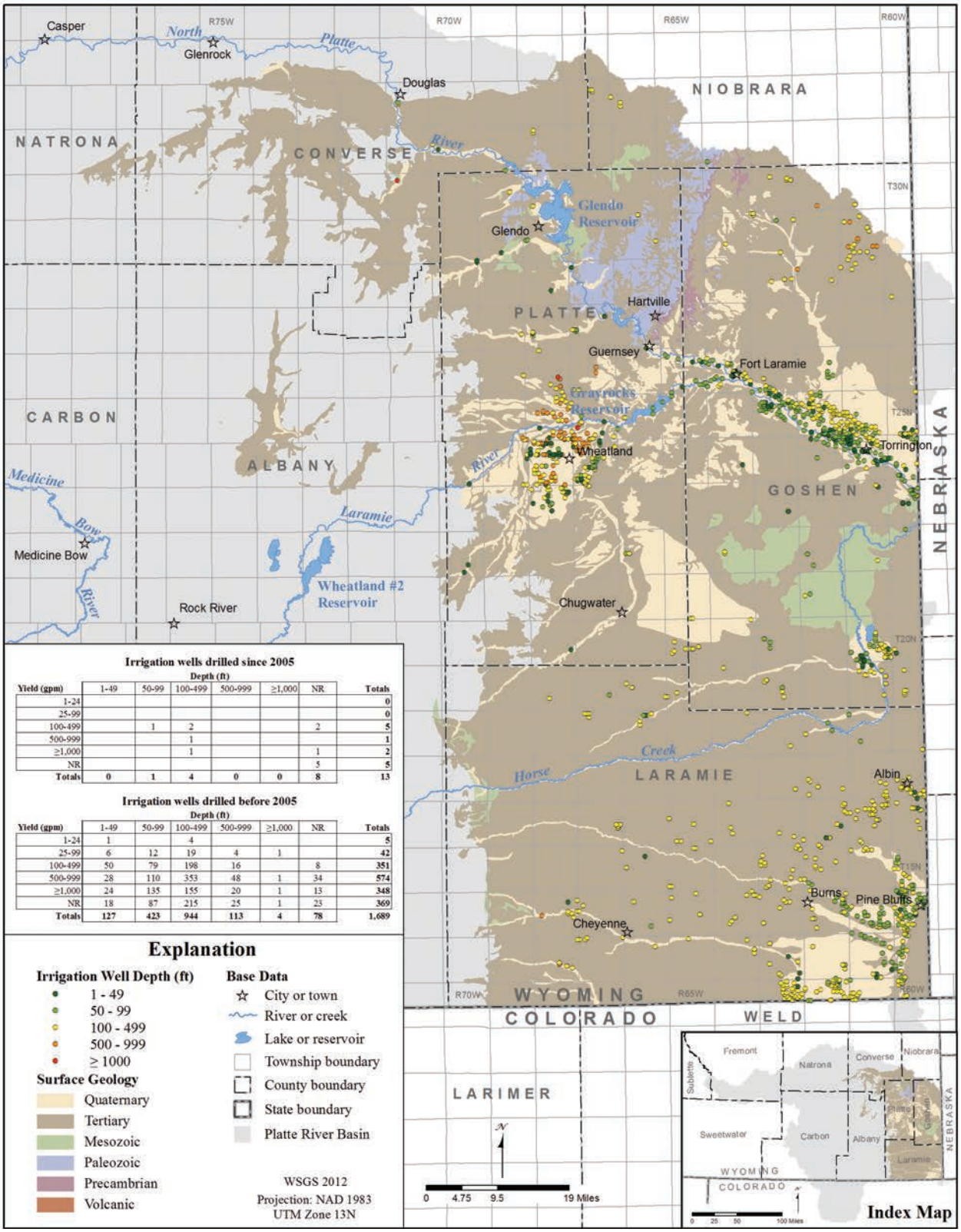
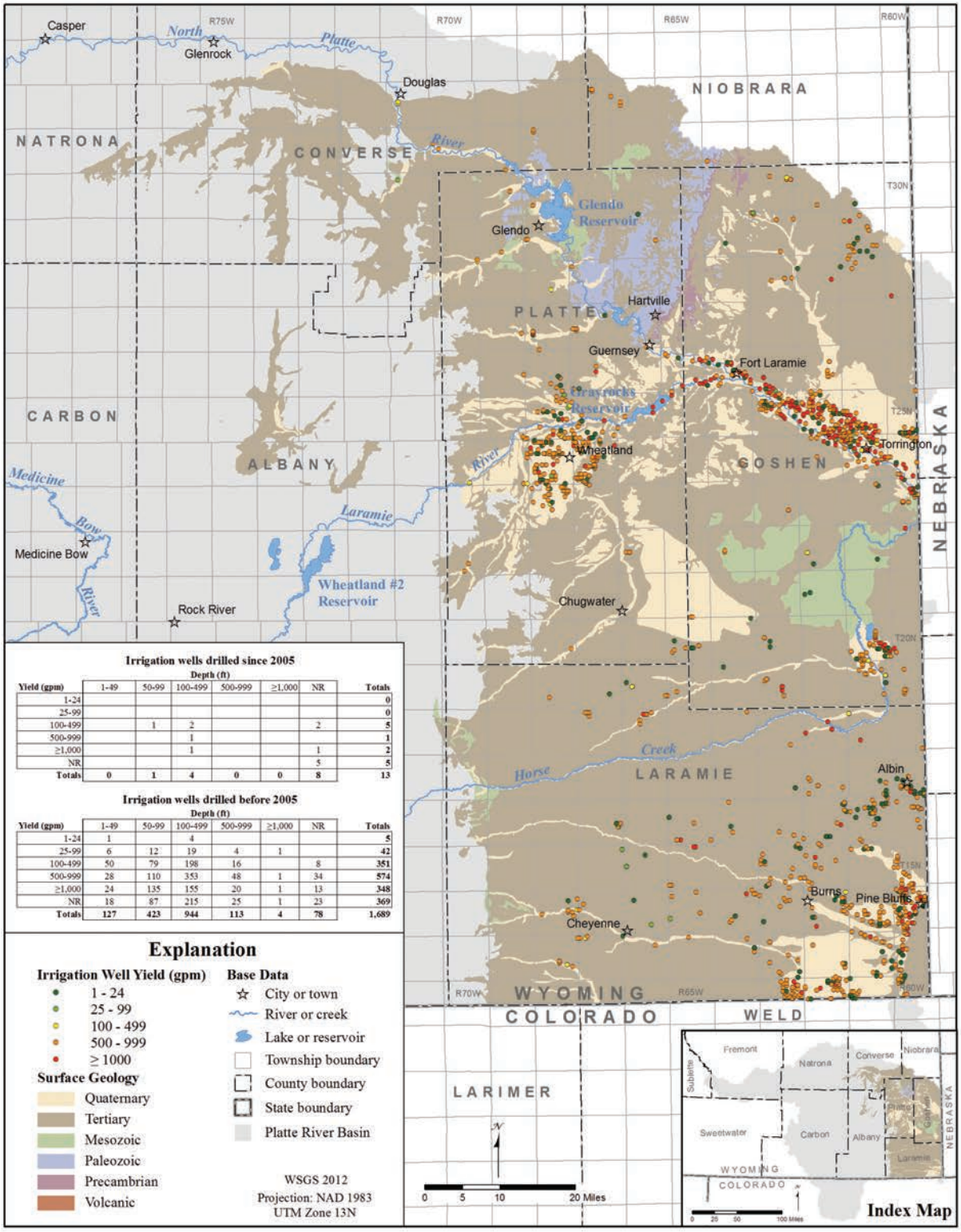


Figure 8-2. Wyoming SEO permitted and drilled irrigation wells in the Denver Basin and Hartville Uplift Subregion.



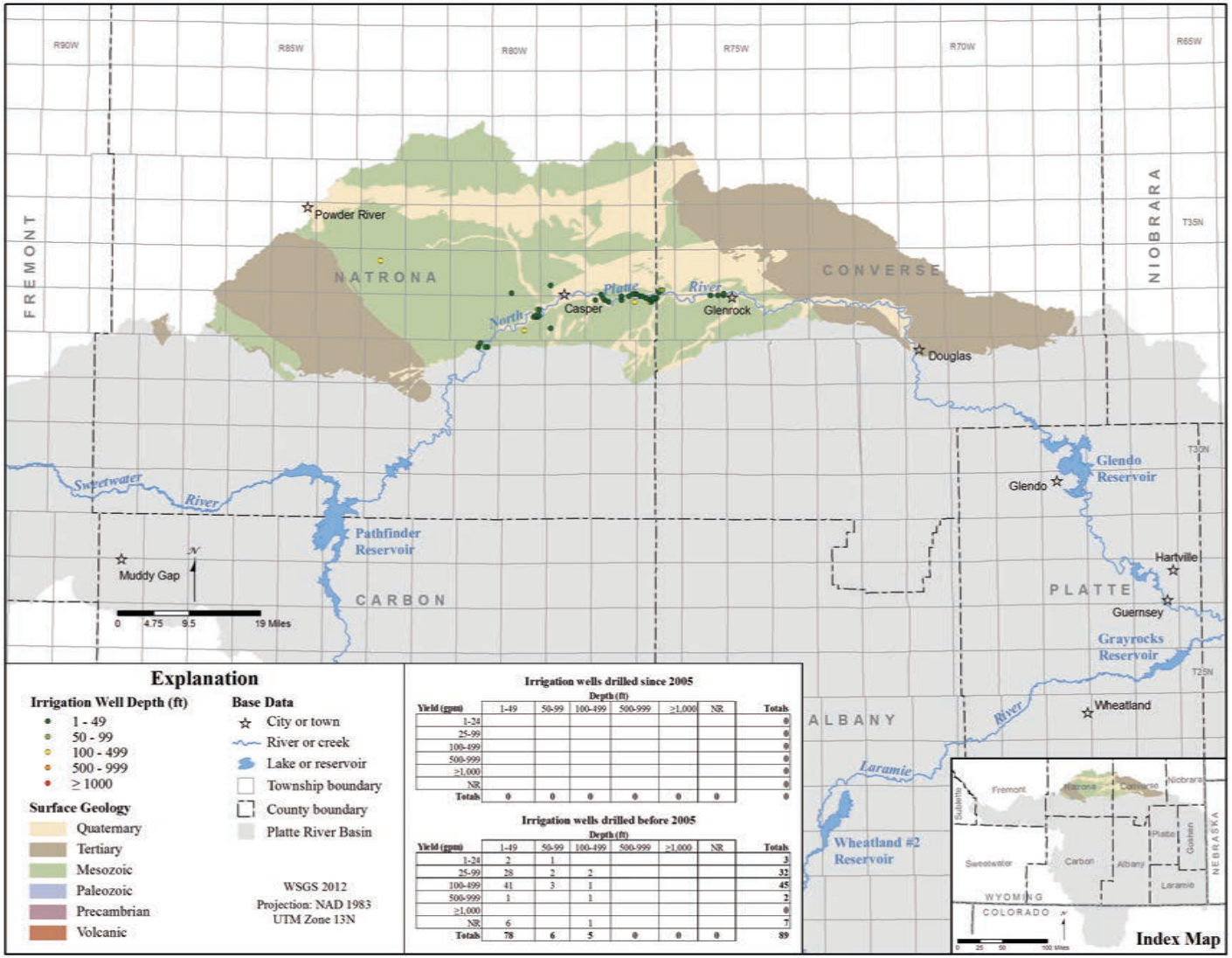
Irrigation wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499		1	2			2	5
500-999			1				1
≥1,000			1			1	2
NR						5	5
Totals	**0**	**1**	**4**	**0**	**0**	**8**	**13**

Irrigation wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1		4				5
25-99	6	12	19	4	1		42
100-499	50	79	198	16		8	351
500-999	28	110	353	48	1	34	574
≥1,000	24	135	155	20	1	13	348
NR	18	87	215	25	1	23	369
Totals	**127**	**423**	**944**	**113**	**4**	**78**	**1,689**

Figure 8-3. Wyoming SEO permitted and drilled irrigation wells in the Denver Basin and Hartville Uplift Subregion.



Irrigation wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR							0
Totals	0	0	0	0	0	0	0

Irrigation wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	2	1					3
25-99	28	2	2				32
100-499	41	3	1				45
500-999	1		1				2
≥1,000							0
NR	6		1				7
Totals	78	6	5	0	0	0	89

Figure 8-4. Wyoming SEO permitted and drilled irrigation wells in the Casper Arch, Wind River and Powder River Basins Subregion.

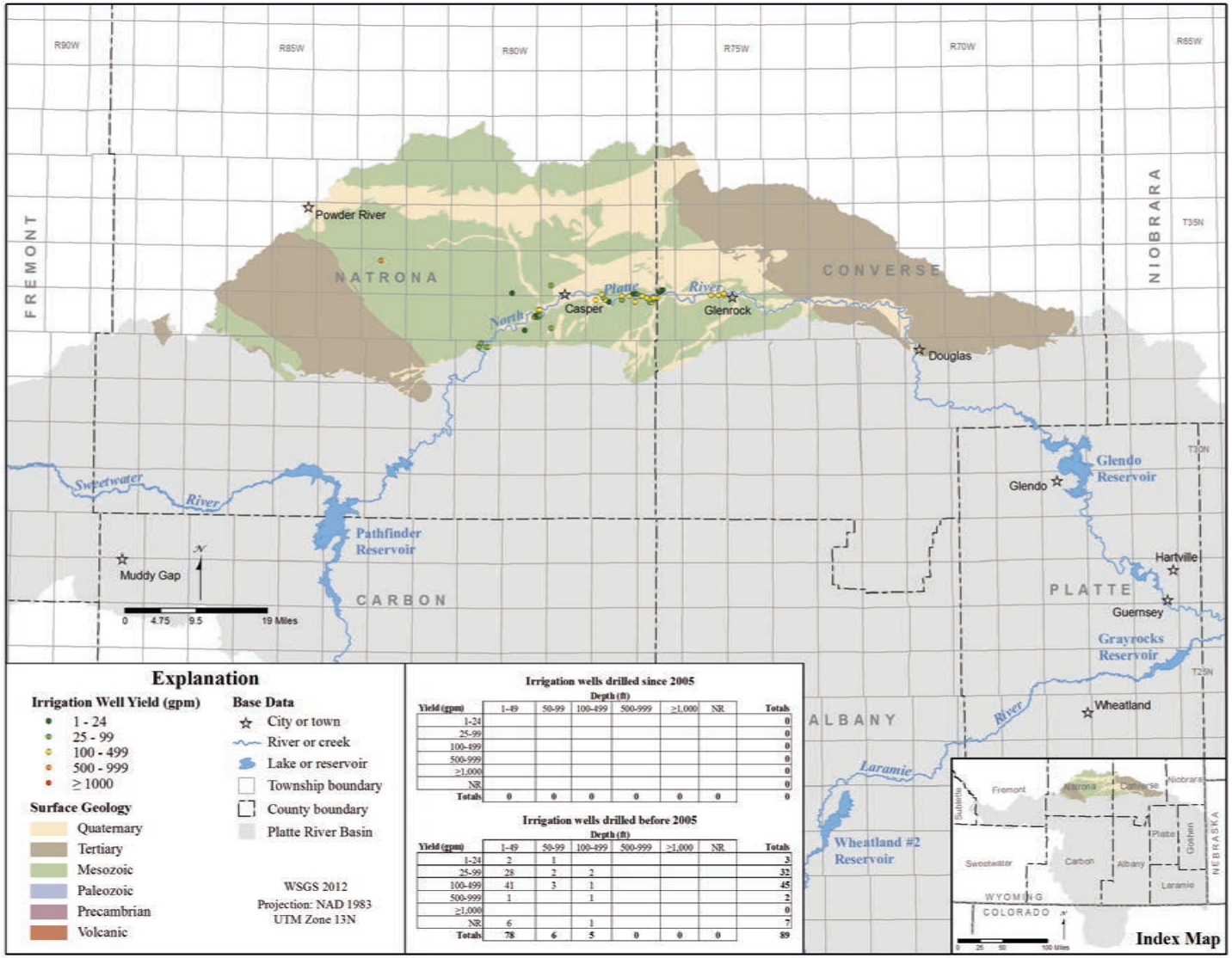
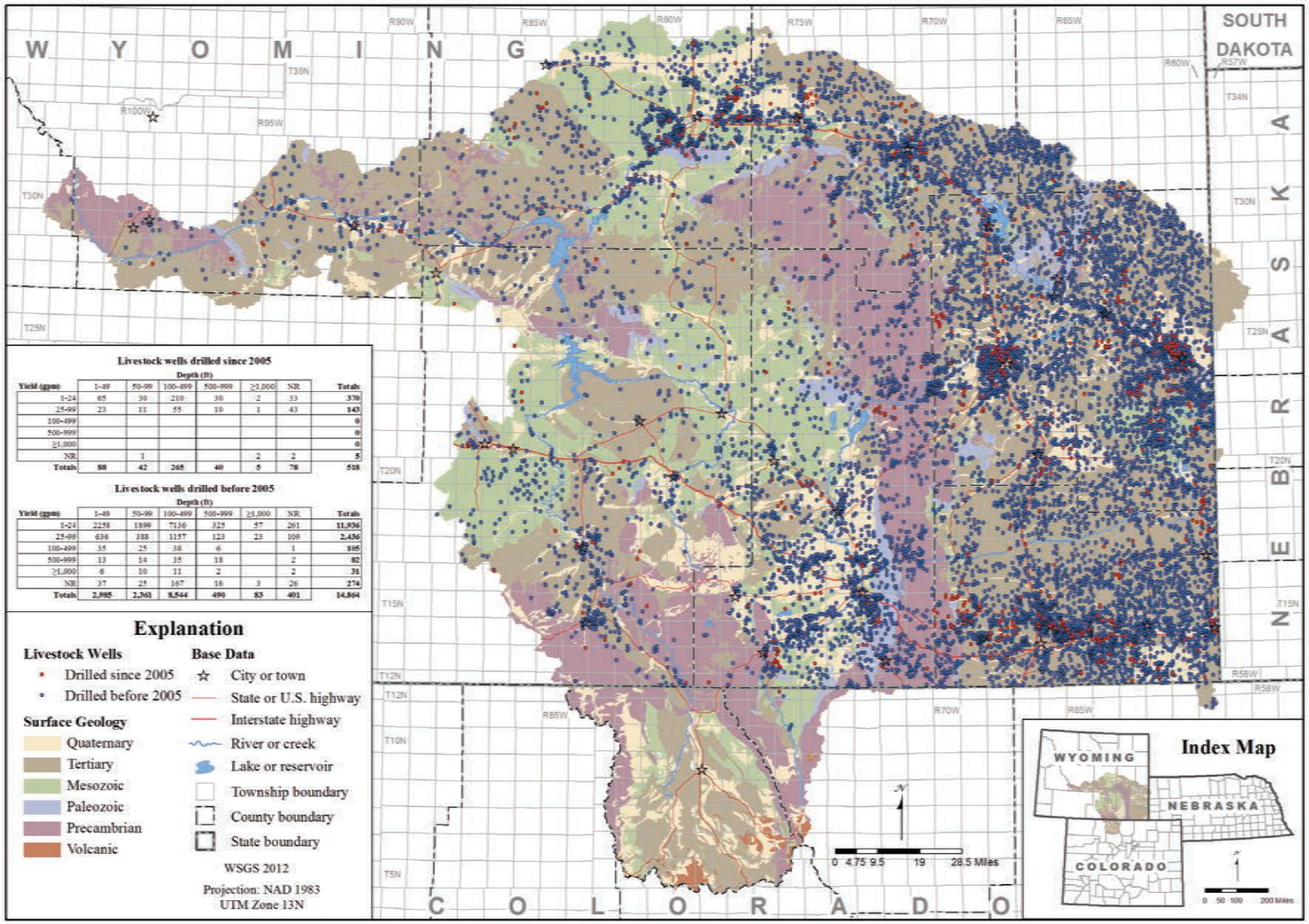


Figure 8-5. Wyoming SEO permitted and drilled irrigation wells in the Casper Arch, Wind River and Powder River Basins Subregion.



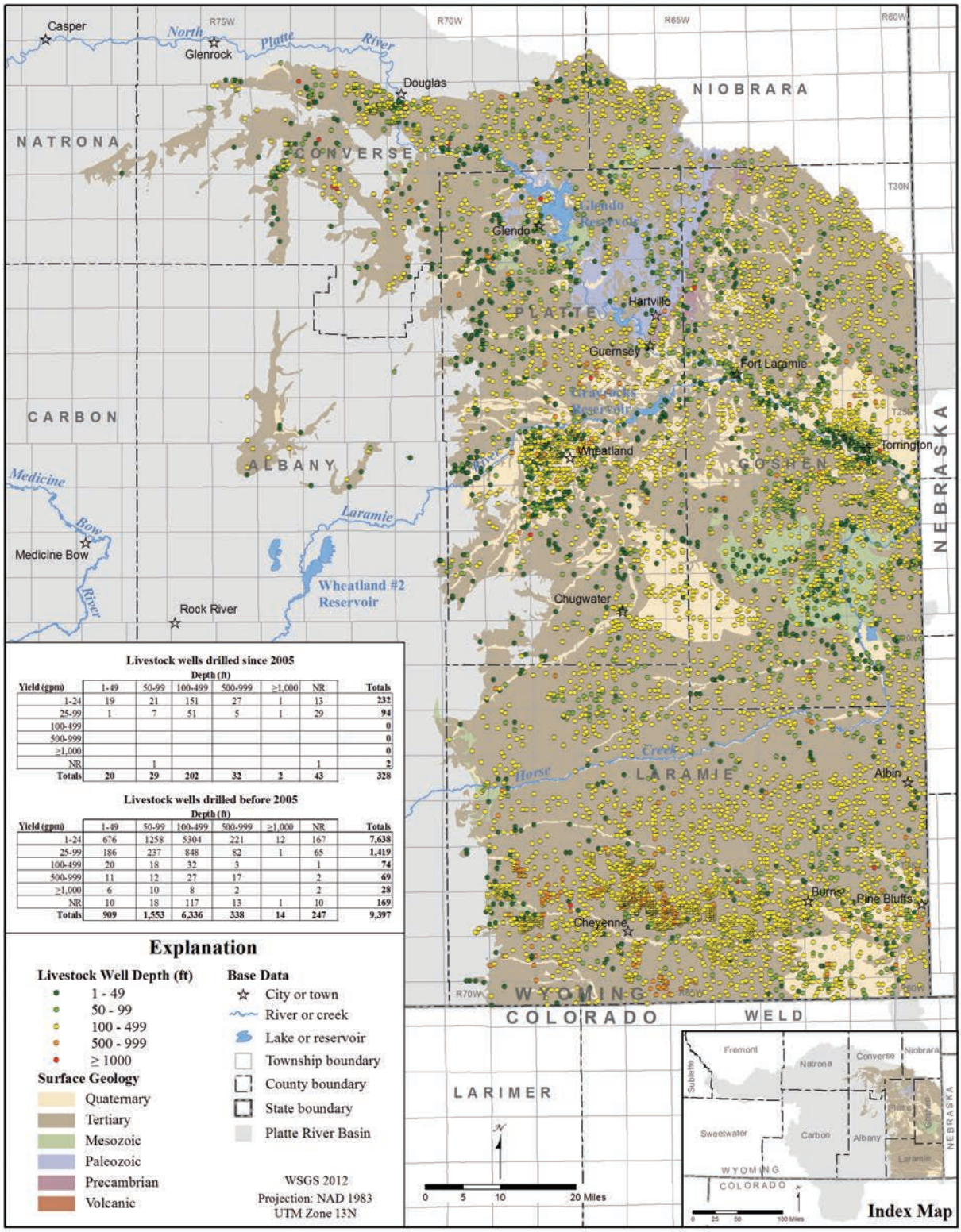
Livestock wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	65	30	210	30	2	33	370
25-99	23	11	55	10	1	43	143
100-499							0
500-999							0
≥1,000							0
NR		1			2	2	5
Totals	88	42	265	40	5	78	518

Livestock wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	2258	1899	7136	325	57	261	11,936
25-99	636	388	1157	123	23	109	2,436
100-499	35	25	38	6		1	105
500-999	13	14	35	18		2	82
≥1,000	6	10	11	2		2	31
NR	37	25	167	16	3	26	274
Totals	2,985	2,361	8,544	490	83	401	14,864

Figure 8-6. Wyoming SEO, Colorado DWR, and Nebraska DNR permitted and drilled livestock wells.



Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	19	21	151	27	1	13	**232**
25-99	1	7	51	5	1	29	**94**
100-499							**0**
500-999							**0**
≥1,000							**0**
NR		1				1	**2**
Totals	**20**	**29**	**202**	**32**	**2**	**43**	**328**

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	676	1258	5304	221	12	167	**7,638**
25-99	186	237	848	82	1	65	**1,419**
100-499	20	18	32	3		1	**74**
500-999	11	12	27	17		2	**69**
≥1,000	6	10	8	2		2	**28**
NR	10	18	117	13	1	10	**169**
Totals	**909**	**1,553**	**6,336**	**338**	**14**	**247**	**9,397**

Figure 8-7. Wyoming SEO permitted and drilled livestock wells in the Denver Basin and Hartville Uplift Subregion.

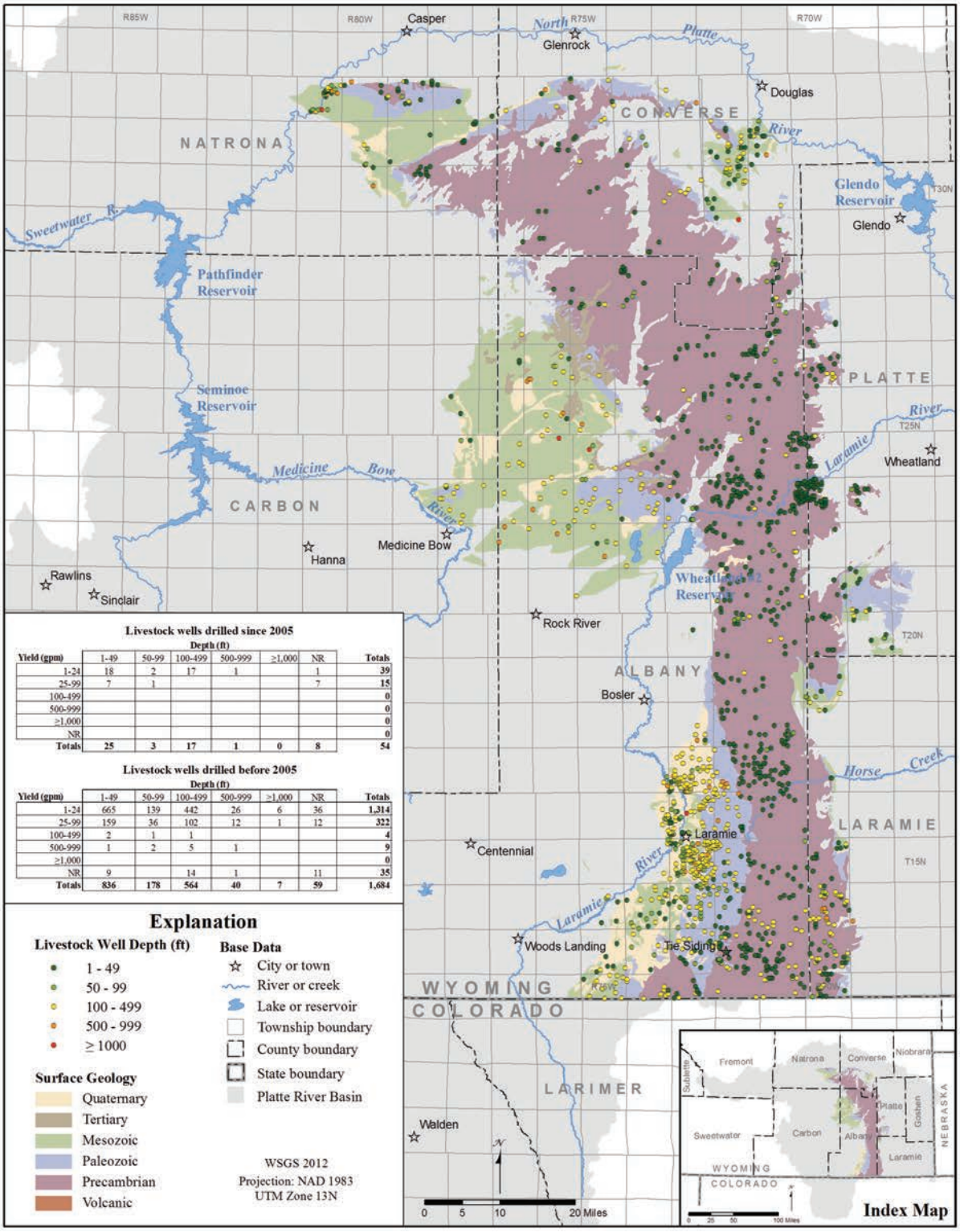


Figure 8-8. Wyoming SEO permitted and drilled livestock wells in the Laramie Mountains and Central Uplifts Subregion.

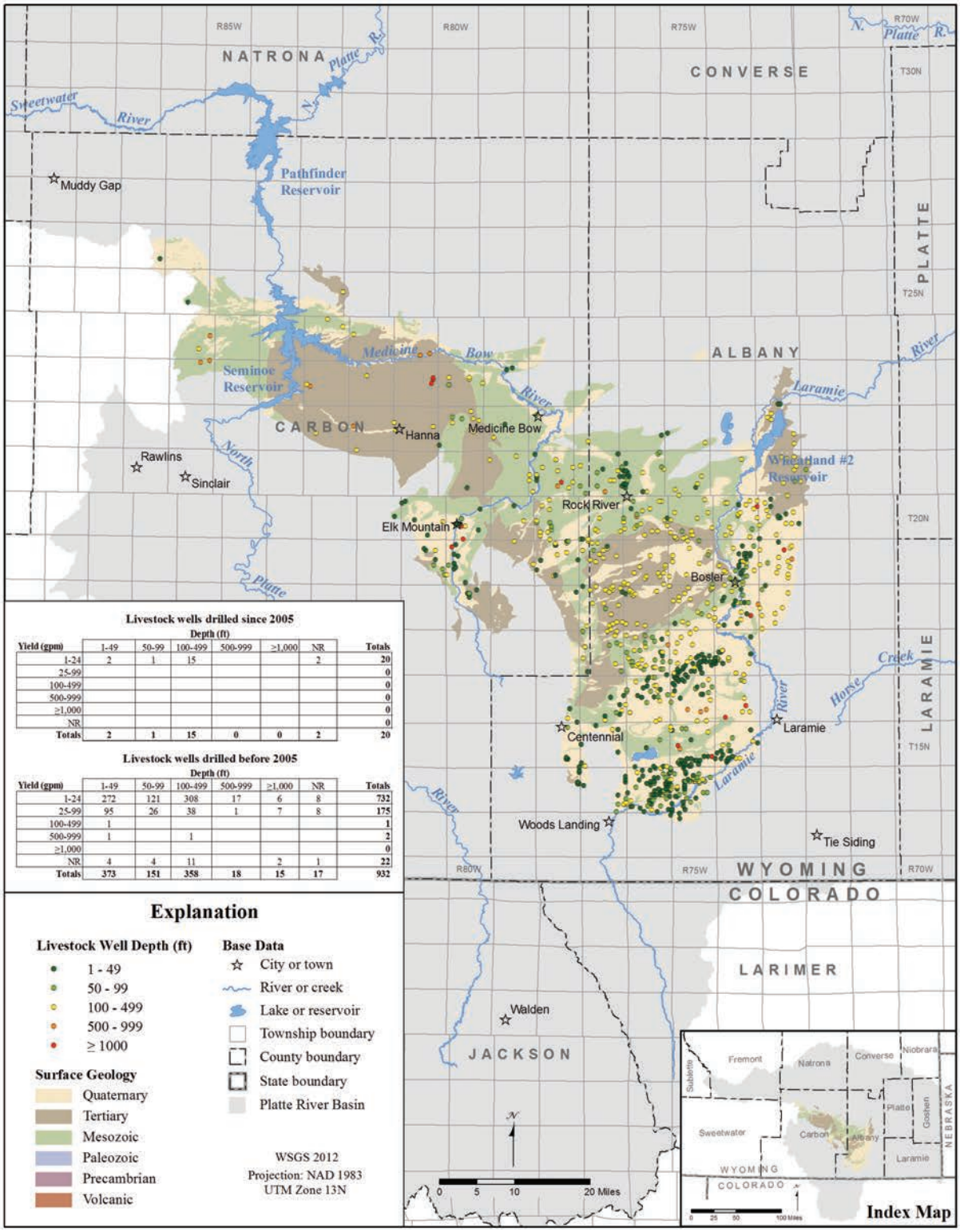
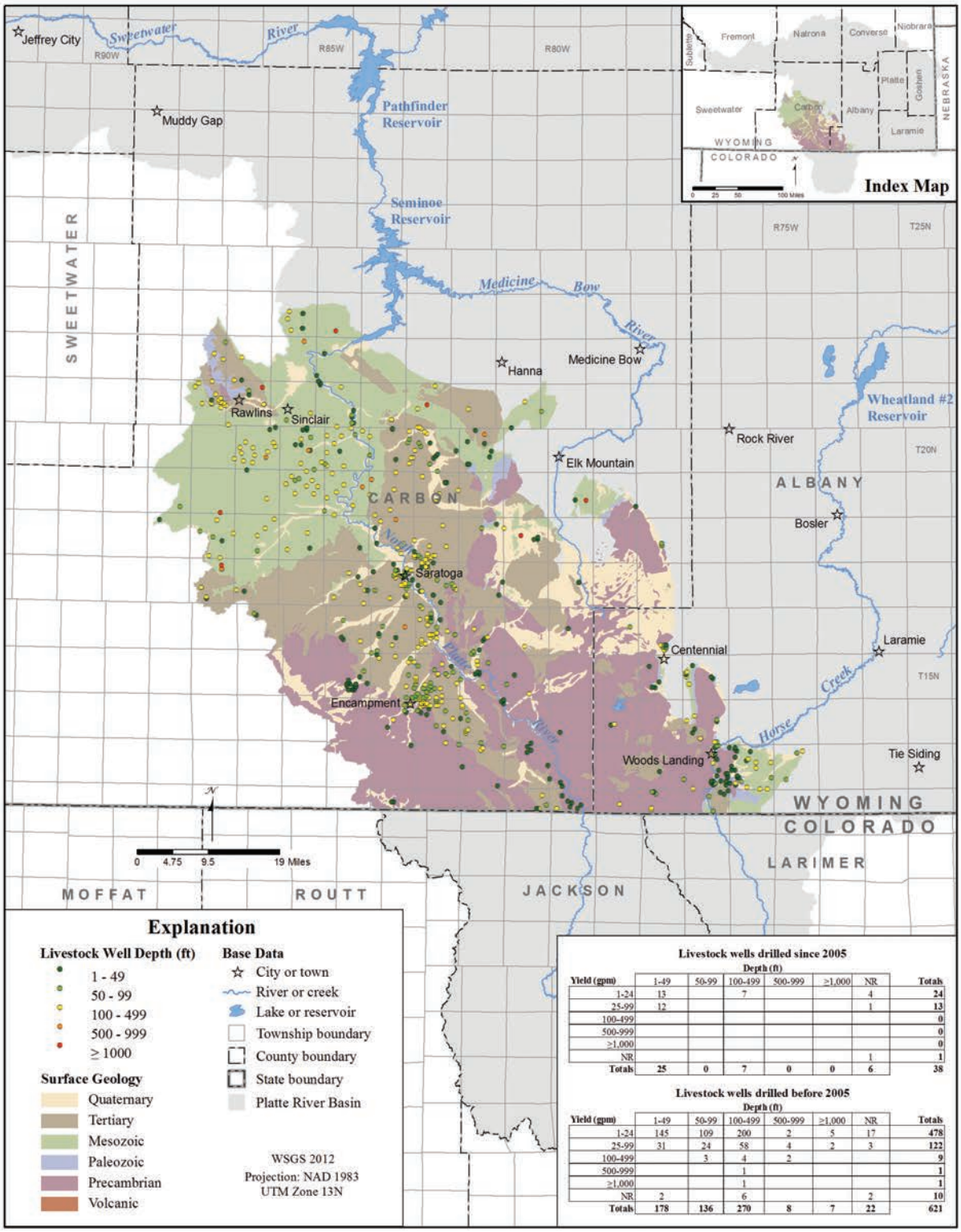


Figure 8-9. Wyoming SEO permitted and drilled livestock wells in the Laramie and Hanna Basins Subregion.



Livestock wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	13		7			4	24
25-99	12					1	13
100-499							0
500-999							0
≥1,000							0
NR						1	1
Totals	25	0	7	0	0	6	38

Livestock wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	145	109	200	2	5	17	478
25-99	31	24	58	4	2	3	122
100-499		3	4	2			9
500-999			1				1
≥1,000			1				1
NR	2		6			2	10
Totals	178	136	270	8	7	22	621

Figure 8-10. Wyoming SEO permitted and drilled livestock wells in the Medicine Bow Mountains and Sierra Madre Subregion.

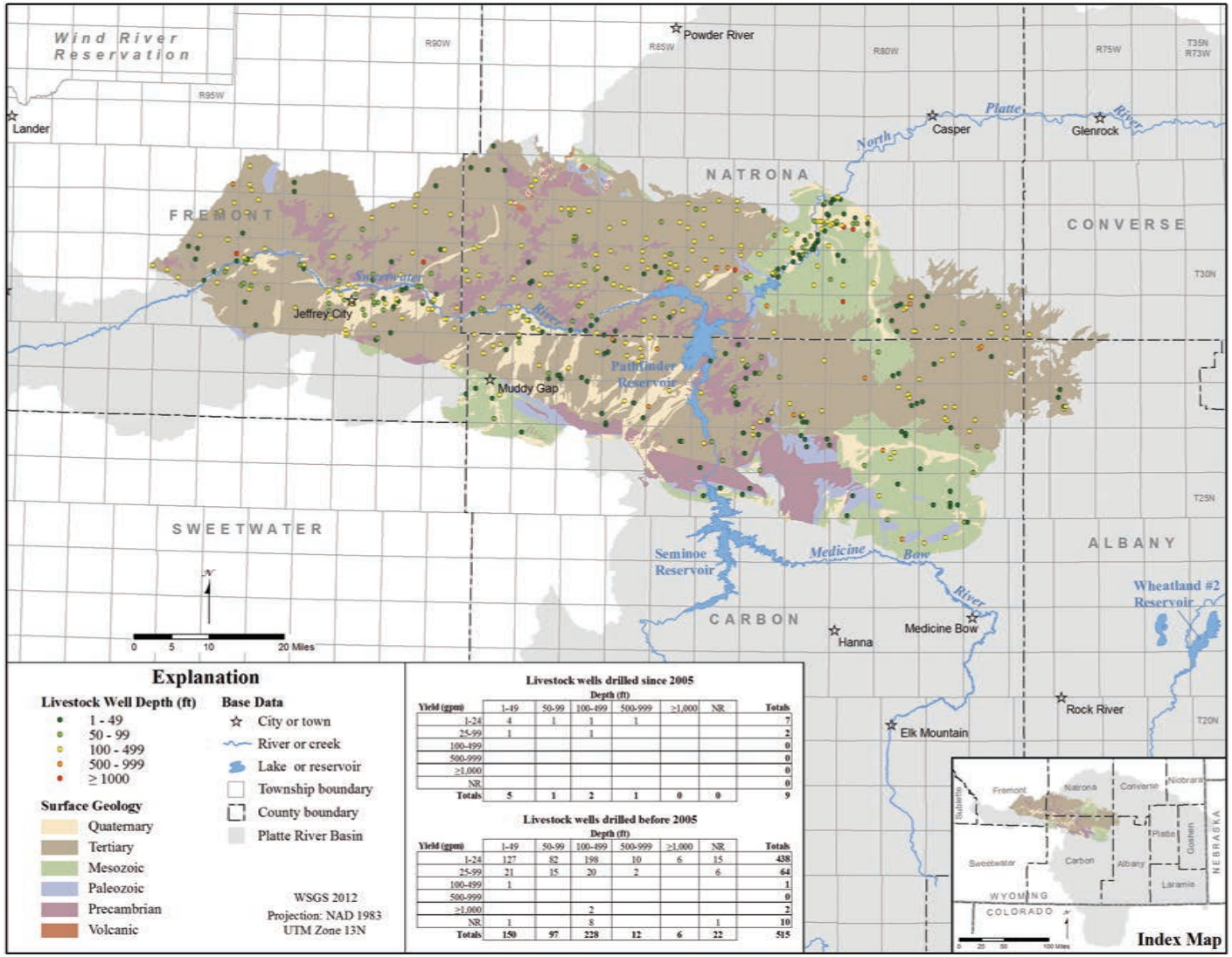
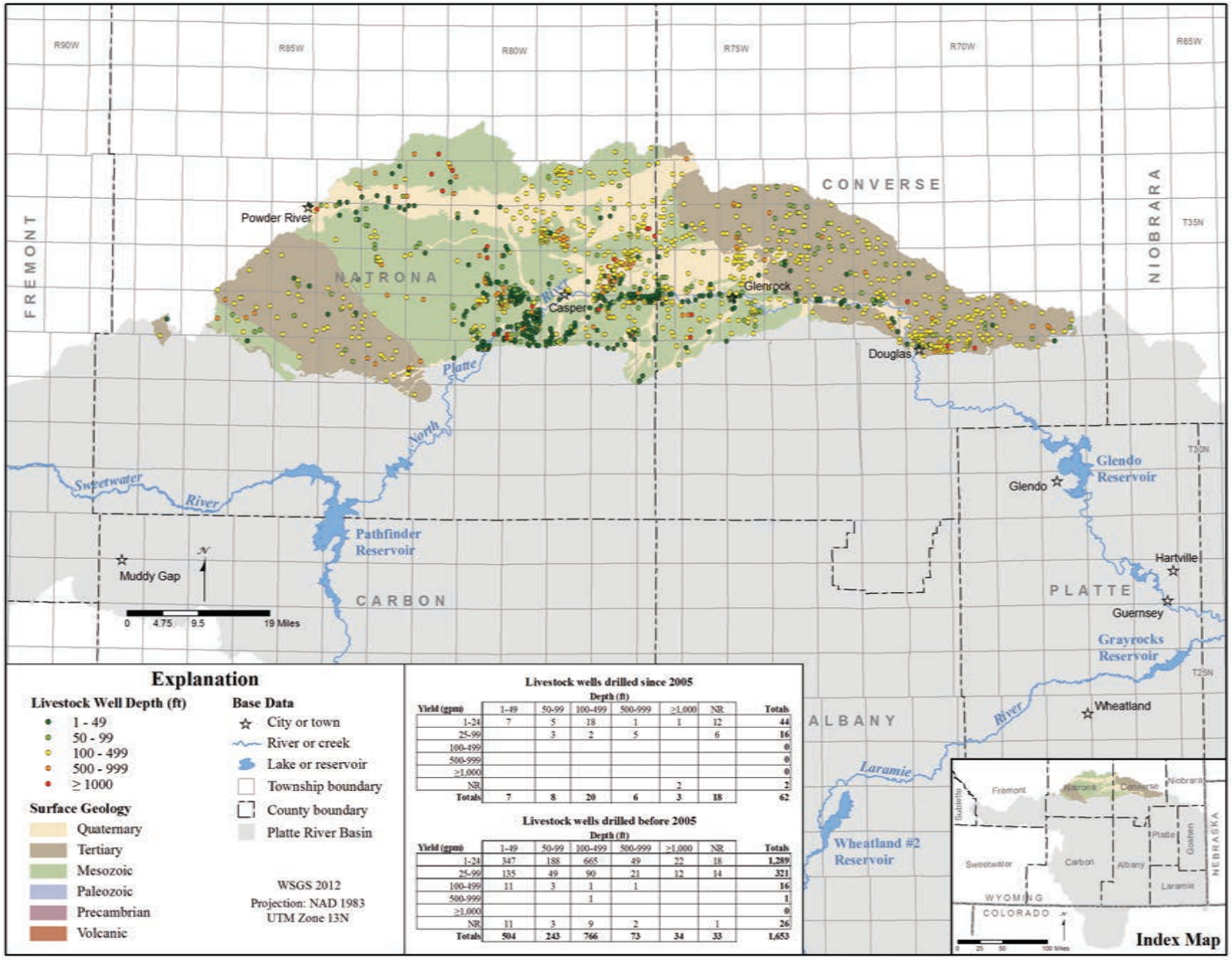


Figure 8-11. Wyoming SEO permitted and drilled livestock wells in the Granite Mountains and Shirley Basin Subregion.



Livestock wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	7	5	18	1	1	12	44
25-99		3	2	5		6	16
100-499							0
500-999							0
>1,000							0
NR					2		2
Totals	**7**	**8**	**20**	**6**	**3**	**18**	**62**

Livestock wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	347	188	665	49	22	18	1,289
25-99	135	49	90	21	12	14	321
100-499	11	3	1	1			16
500-999			1				1
>1,000							0
NR	11	3	9	2		1	26
Totals	**504**	**243**	**766**	**73**	**34**	**33**	**1,653**

Figure 8-12. Wyoming SEO permitted and drilled livestock wells in the Casper Arch, Wind River and Powder River Basins Subregion.

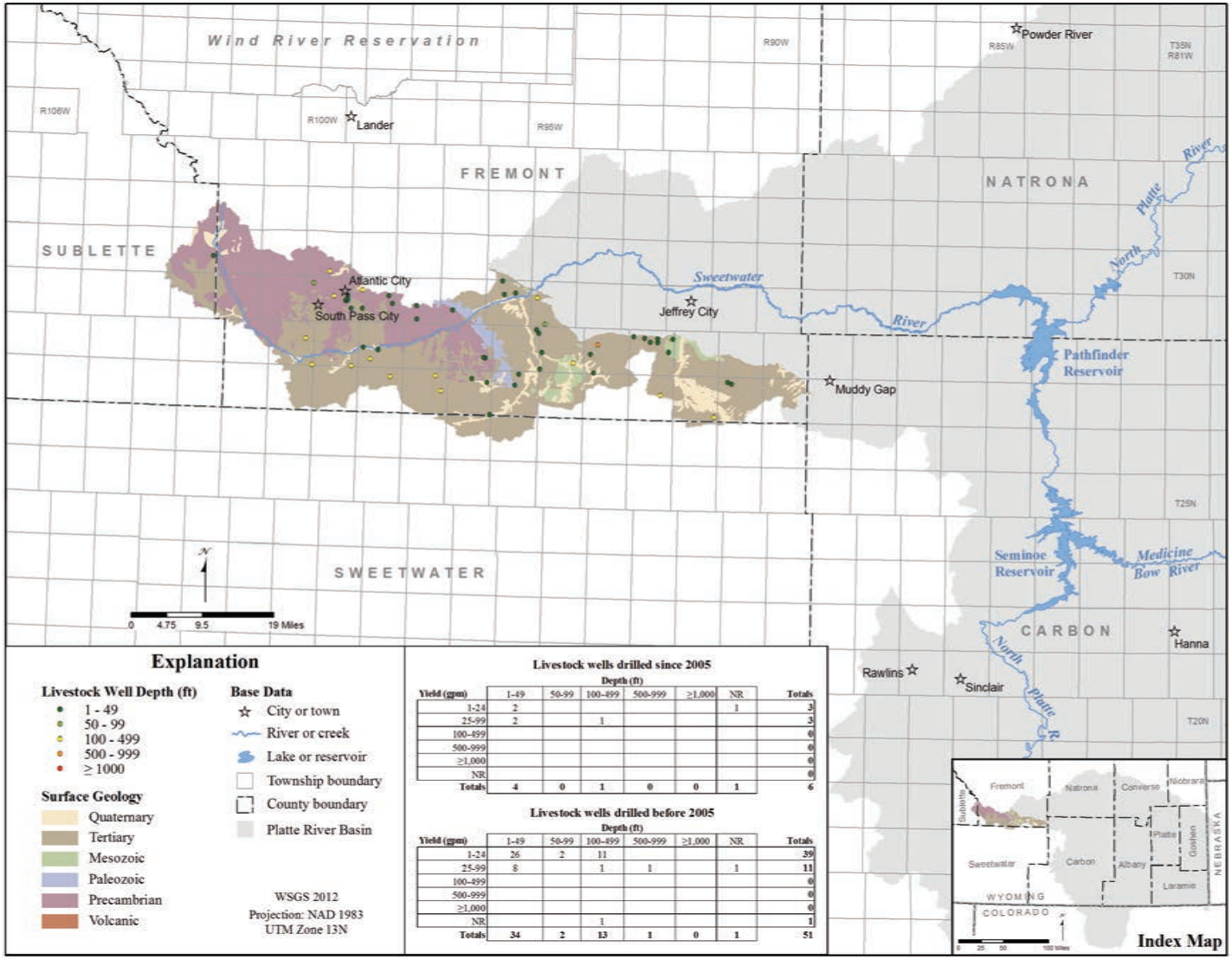


Figure 8-13. Wyoming SEO permitted and drilled livestock wells in the Wind River Mountains and Great Divide Basin Subregion.

up to 100 gpm. A relatively small number of permits for stock watering have no recorded depth or yield information. **Figures 8-6** through **8-13** also show that stock wells have been permitted mostly for relatively shallow depths within virtually all hydrogeologic units, including confining units, across a wide range of surface elevations. This indicates that useful quantities of relatively shallow groundwater can be found at most locations within the Platte River Basin.

8.4.4.3 SEO municipal-use permits

There are 457 groundwater permits for municipal use (MUN) in the Wyoming Platte River Basin with 19 permits issued after January 2005 (**Table 8-6**). **Figure 8-14** shows the spatial distribution of likely drilled SEO municipal wells. The depth vs. yield tables on **Figure 8-14** show 134 municipal-use well permits were issued before and 2 permits were issued after January 2005. Most municipal permits are for yields between 100 and 1000 gpm, and depths of 100 to 500 feet. No municipal-use permits were included in either the CDWR or NDNR data.

Tables 8-9 and 8-10 distinguish by status 519 municipal-use groundwater permits on file with the SEO. **Table 8-9** summarizes selected information on 122 municipal-use permits that have been fully adjudicated; all of these permits were issued before January 2005. **Table 8-9** includes available information on permitted yield, well depth, depth of the producing interval, and the producing hydrogeologic unit. Four of the permits in **Table 8-9** are for multiple uses. Because the "fully adjudicated" permit status indicates that the well has been inspected, the information in **Table 8-9** is presumed to be fairly accurate. The wells in **Table 8-9** produce water from alluvial and bedrock aquifers, **(Plate 2)**. Information on producing intervals was obtained from WDEQ SWAP data, WWDC consultant reports and SEO data.

Table 8-10 summarizes information for 397 municipal well permits that have statuses other than "adjudicated". Fifty eight of the permits in **Table 8-10** are for multiple uses. While cancelled permits may or may not be associated with a completed well, abandoned status generally refers to a previously existing well. **Table 8-10** includes available information on yield and well depth. Permits with the most information, especially those that include the depth of the producing interval (which is generally provided by the well owner after the well has been completed) are most likely to be associated with completed wells.

8.4.4.4 Domestic-use permits (Figures 8-6 through 8-22)

Domestic water withdrawals include non–community public water systems and rural domestic users. **Tables 8-6, 8-7,** and **8-8** show that groundwater permits for domestic use (DOM) outnumber permits for all other uses combined, with 15,902 SEO permits, 164 CDWR permits (including 30 household-use permits), and 1 NDNR permit.

Figure 8-15 shows the distribution of likely drilled domestic-use permits in the entire Platte River Basin issued before and after January 2005. **Figures 8-16** through **8-22** map the distribution of domestic wells over five ranges of well depth within the seven subregions of the Platte River Basin (**Chapter 2**). Most domestic wells are located in rural areas, generally outlying population centers along rivers and other surface drainages, where groundwater is the only reliable source of water. Most wells are completed in Quaternary and Tertiary geologic units; however, domestic-use wells have also been permitted over a wide range of depths within virtually all hydrogeologic units (including confining units) throughout the Platte River Basin, pointing to the fact that useful quantities of relatively shallow groundwater can be found at many locations and that the distribution of recharge is widespread. The depth vs. yield tables on **Figure 8-15** show that basin-wide, the largest percentage of both classes of permits (issued before and since January 2005) allow well depths up to 999 feet and yields up to 99 gpm. Few domestic-use permits do not provide any recorded depth and/or yield information.

8.4.4.5 Source Water Assessment Program (SWAP) wells and springs (Figure 8-23)

The SWAP, a component of the federal Safe Drinking Water Act, is designed to help states protect

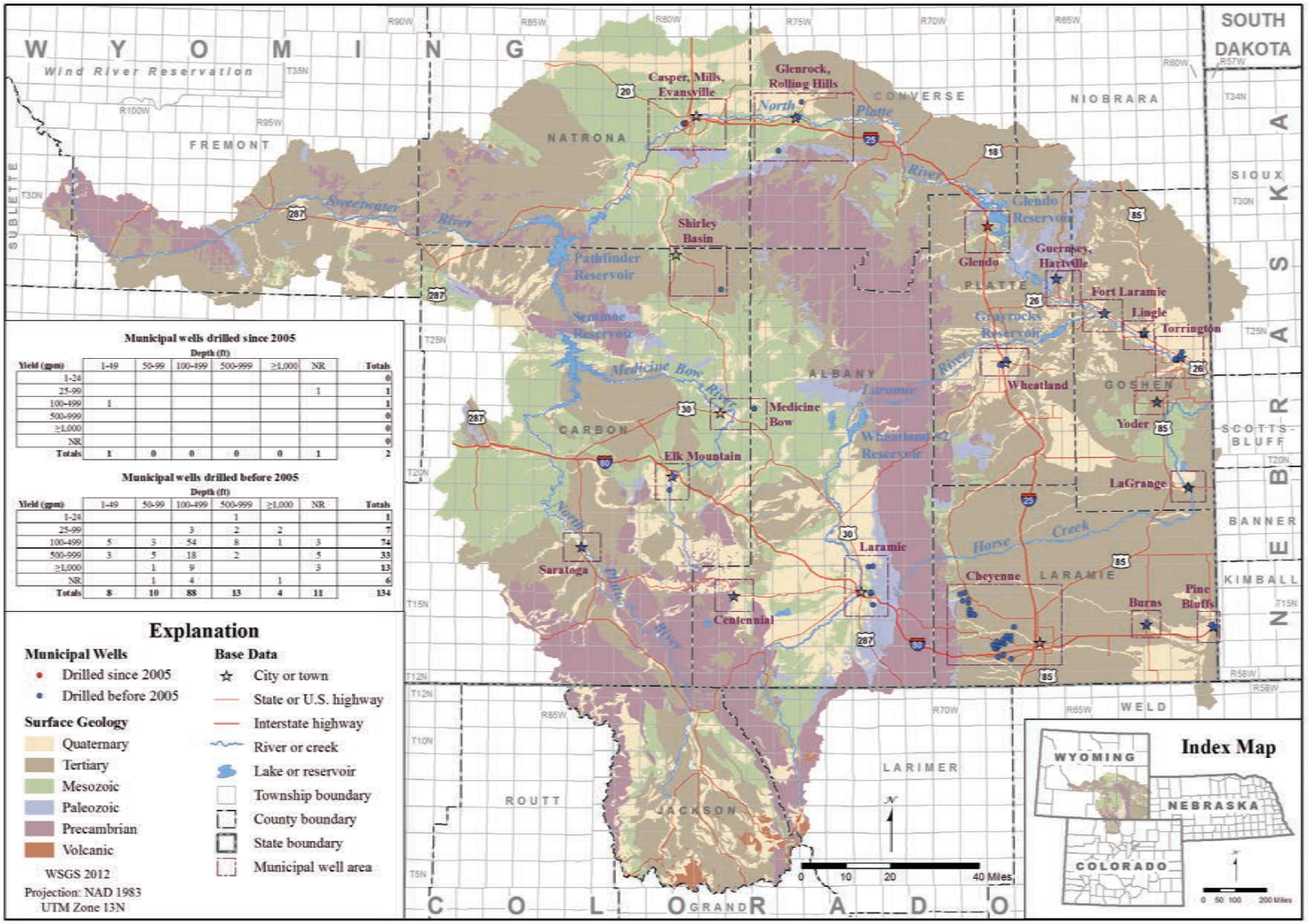


Figure 8-14. Wyoming SEO permitted and drilled municipal wells.

Table 8-9 WSEO fully adjudicated well permits in the Wyoming PtRB database by municipal use.

Municipality or Community	Well Name	WSEO Permit Number	Permit yield (gpm)	Well Depth (feet)	Permit Status	Hydro-geologic unit	Multi-use	Depth of Producing Interval (feet)
Burns	A 4 WATER	P37502.0W	850	235	Fully Adjudicated	Ogallala Fm, Arikaree Fm, and White River Fm		
Burns	A-1 WATER	P1358.0W	100	232	Fully Adjudicated			
Burns	A-2 WATER WELL	P1360.0W	325	200	Fully Adjudicated	Ogallala Fm, Arikaree Fm, and White River Fm		
Burns	A3 WATER WELL	P9110.0W	150	250	Fully Adjudicated			
Centennial	CENTENNIAL WELL #1	P81280.0W	45	740	Fully Adjudicated	Casper Fm		
Centennial	CENTENNIAL WELL #2	P83020.0W	50	860	Fully Adjudicated	Casper Fm		
Centennial	ENL CENTENNIAL #2	P89526.0W	15	860	Fully Adjudicated	Casper FM		
Cheyenne	CHEYENNE #13 (HOLMAN WELL #1)	P265.0C	475	370	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #15 (ELKAR WELL #1)	P266.0C	300	454	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #20 (BAILEY #5)	P268.0C	125	317	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #22 (EDDY #2)	P269.0C	250	335	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #25 (KOPPES #1)	P270.0C	325	305	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #26 (KOPPES #2)	P271.0C	375	331	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #30 (HAPPY JACK #3)	P275.0C	250	300	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #31 (MERRITT #1)	P276.0C	200	308	Fully Adjudicated			
Cheyenne	CHEYENNE #36 (MERRITT #5)	P278.0C	200	184	Fully Adjudicated	White River Fms		
Cheyenne	CHEYENNE #37 (MERRITT #6)	P279.0C	150	178	Fully Adjudicated	White River Fms		
Cheyenne	CHEYENNE #44 (ELKAR #5)	P282.0C	500	410	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #48 (KING #2)	P284.0C	150	150	Fully Adjudicated	Ogallala		
Cheyenne	CHEYENNE #50 (ELKAR WELL #7)	P285.0C	375	291	Fully Adjudicated	Ogallala		
Cheyenne	CHEYENNE #51 (FINNERTY #2)	P286.0C	350	384	Fully Adjudicated	Ogallala		
Cheyenne	CHEYENNE #52 (KING #4)	P287.0C	250	350	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #54 (KING #5)	P289.0C	275	395	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #55 (KOPPES WELL #6)	P290.0C	200	270	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #56 (BORIE #1)	P291.0C	300	352	Fully Adjudicated	Ogallala and White River Fms		
Cheyenne	CHEYENNE #57 (WEBER #1)	P13.0G	400	395	Fully Adjudicated			
Cheyenne	CHEYENNE #58 (CONREY #1)	P14.0G	225	300	Fully Adjudicated			
Cheyenne	CHEYENNE No.47 (KING No. 1)	P95498.0W	275	360	Fully Adjudicated			
Cheyenne	ENL BORIE #1 (CHEYENNE #56)	P101352.0W	600	352	Fully Adjudicated			
Cheyenne	ENL CHEYENNE #44 (ELKAR #5)	P84177.0W	250	410	Fully Adjudicated			
Cheyenne	ENL EDDY #2 (CHEYENNE #22)	P101348.0W	100	335	Fully Adjudicated			
Cheyenne	ENL ELKAR No. 7 (CHEYENNE No. 50)	P101350.0W	325	291	Fully Adjudicated			
Cheyenne	ENL KING #4 (CHEYENNE #52)	P101351.0W	250	350	Fully Adjudicated			
Cheyenne	ENL KOPPES N0. 1 (CHEYENNE No. 25)	P101349.0W	175	305	Fully Adjudicated			
Cheyenne	ENL MERRITT #14	P84176.0W	100	245	Fully Adjudicated	White River Fm		
Cheyenne	ENL. MERRITT #5 WELL	P90865.0W	150	184	Fully Adjudicated			
Cheyenne	MERRITT #14 WELL	P342.0G	150	245	Fully Adjudicated	White River Fm		
Cheyenne	MERRITT #15 WELL	P257.0G	350	222	Fully Adjudicated	White River Fm		
Cheyenne	MERRITT #8	P256.0G	325	188	Fully Adjudicated	White River Fms		
Cheyenne	MERRITT #9 WELL	P341.0G	320	250	Fully Adjudicated	White River,Lance, & Fox Hills Fms		
Cheyenne	SCHOOL #1	P258.0G	225	294	Fully Adjudicated	Ogallala		
Cheyenne	SCHOOL #2	P340.0G	425	354	Fully Adjudicated			
Elk Mountain	ELK MOUNTAIN #2	P47305.0W	30	2,475	Fully Adjudicated	Cloverly Group		2367-2394
						Cloverly Group		2790-2800
Elk Mountain	ELK MOUNTAIN WELL #3	P103496.0W	127	2,963	Fully Adjudicated	Dakota/Lakota		2810-2890
Fort Laramie	FORT LARAMIE #2	P2066.0W	500	82	Fully Adjudicated	Alluvium		42-82
Fort Laramie	FT. LARAMIE #1 WELL	P95.0G	825	80	Fully Adjudicated	Alluvium		
Glenrock	FOX HILLS #1	P44473.0W	125	508	Abandoned			
LaGrange	ENL LAGRANGE #2	P74020.0W	125	100	Fully Adjudicated		Yes	
LaGrange	ENL WENDT	P3799.0W	0	151	Fully Adjudicated			
LaGrange	LAGRANGE #1	P55678.0W	450	100	Fully Adjudicated	White River Fm-Brule Member, locally includes upper conglomerate member	Yes	
LaGrange	LAGRANGE #2	P55679.0W	450	100	Fully Adjudicated	White River Fm-Brule Member, locally includes upper conglomerate member	Yes	
Laramie	ENL POPE #4 WELL	P72692.0W	50	350	Fully Adjudicated	Casper Fm		65-350
Laramie	ENL POPE #2	P72690.0W	75	162	Fully Adjudicated	Casper Fm		
Laramie	ENL POPE #3	P72691.0W	50	158	Fully Adjudicated	Casper Fm		
Laramie	ENL POPE #3	P55505.0W	250	158	Fully Adjudicated	Casper Fm		
Laramie	ENL TURNER #1	P72689.0W	300	240	Fully Adjudicated	Casper Fm		
Laramie	ENL TURNER #1	P61724.0W	800	240	Fully Adjudicated	Casper Fm		
Laramie	ENL TURNER #2	P59131.0W	200	350	Fully Adjudicated	Casper Fm		
Laramie	POPE #1	P153.0C	550	156	Fully Adjudicated	Casper Fm		
Laramie	POPE #2	P154.0C	515	162	Fully Adjudicated	Casper Fm		
Laramie	POPE #3	P155.0C	590	158	Fully Adjudicated	Casper Fm		
Laramie	POPE #4	P55506.0W	1,750	350	Fully Adjudicated	Casper Fm		
Laramie	SPUR #1	P106547.0W	2,500	305	Fully Adjudicated	Casper Fm		
Laramie	SPUR #2	P115181.0W	2,500	323	Fully Adjudicated	Casper Fm		
Laramie	TURNER #1	P55507.0W	1,400	240	Fully Adjudicated	Casper Fm		
Laramie	TURNER #2	P55508.0W	1,400	350	Fully Adjudicated	Casper Fm		
Lingle	ENL WELL #6	P78253.0W	600	78	Fully Adjudicated	Alluvium and White River Fm		
Lingle	LINGLE #4	P629.0W	600	82	Fully Adjudicated	Alluvium and White River Fm		
Lingle	LINGLE #5	P8564.0W	475	70	Fully Adjudicated	Alluvium and White River Fm		
Lingle	WELL #6	P41620.0W	500	78	Fully Adjudicated	Alluvium and White River Fm		
Medicine Bow	COMO #4	P69012.0W	600	660	Fully Adjudicated	Casper Fm		
Medicine Bow	COMO WELLS	P399.0C	139	800	Fully Adjudicated	Casper Fm		
Medicine Bow	ENL COMO WELLS	P84302.0W	211	800	Fully Adjudicated	Casper Fm	Yes	
Mills	MILLS #1	P1252.0W	300	40	Fully Adjudicated	Alluvium		
Mills	MILLS #2	P1253.0W	300	40	Fully Adjudicated	Alluvium		
Mills	MILLS #3	P1254.0W	500	38	Fully Adjudicated	Alluvium		
Mills	MILLS WELL #5	P4588.0W	600	40	Fully Adjudicated	Alluvium		
Mills	MILLS WELL #6	P50607.0W	450	40	Fully Adjudicated	Alluvium		
Pine Bluffs	EKXTROM #1	P298.0C	1,110	60	Fully Adjudicated	White River Fm, Brule member		
Pine Bluffs	ENL OF THE PINE BLUFFS MUNICIPAL WELL	P13171.0W	375	125	Fully Adjudicated	White River Fm, Brule member		20-125
Pine Bluffs	FOUR (4)	P13170.0W	850	130	Fully Adjudicated	White River Fm, Brule member		
Pine Bluffs	PINE BLUFFS #2 WELL	P124.0G	325	125	Fully Adjudicated	White River Fm, Brule member		
Pine Bluffs	PINE BLUFFS #5	P3994.0W	750	120	Fully Adjudicated	White River Fm, Brule member		36-120
Pine Bluffs	PINE BLUFFS MUNICIPAL	P295.0C	375	125	Fully Adjudicated	White River Fm, Brule member		
Saratoga	SARATOGA HOBO POOL WELL #1	P1196.0W	130	35	Fully Adjudicated			
Shirley Basin	SHIRLEY BASIN WELL #1	P4385.0W	225	233	Fully Adjudicated			
Shirley Basin	SHIRLEY BASIN WELL #2	P31944.0W	200	235	Fully Adjudicated			

public water systems (PWSs) and applies to both municipal and non-community public systems. The voluntary program, administered by the WDEQ Water Quality Division (WQD), encourages the development of source-water assessments and Wellhead Protection Plans (WHPs) for groundwater PWSs. A source-water assessment entails determining the source-water contributing area, inventorying potential sources of contamination to the PWS(s), determining the susceptibility of the PWS(s) to identified potential contaminants, and summarizing the information in a report. An important aspect of these reports relative to this study is that the producing hydrogeologic unit is commonly identified.

Table 8-9 WSEO fully adjudicated well permits in the Wyoming PtRB database by municipal use.

Municipality or Community	Well Name	WSEO Permit Number	Permit yield (gpm)	Well Depth (feet)	Permit Status	Hydro-geologic unit	Multi-use	Depth of Producing Interval (feet)
Torrington	1ST ENL CITY OF TORRINGTON NEW NO. 5	P71692.0W	100	200	Fully Adjudicated			
Torrington	1ST ENL. CITY OF TORRINGTON NEW NO. 3	P440.0C	800	161	Fully Adjudicated	Alluvium		
Torrington	1ST ENL. CITY OF TORRINGTON NEW NO. 4	P2629.0W	1,000	200	Fully Adjudicated	Alluvium		
Torrington	2ND ENL. CITY OF TORRINGTON NEW NO. 3	P156.0G	750	161	Fully Adjudicated			
Torrington	2ND ENL. CITY OF TORRINGTON NEW NO. 4	P45139.0W	600	200	Fully Adjudicated	Alluvium		
Torrington	2ND ENL. CITY OF TORRINGTON NEW NO. 5	P65949.0W	1,000	200	Fully Adjudicated	Alluvium		
Torrington	3RD ENL CITY OF TORRINGTON NEW NO. 5	P78576.0W	175	200	Fully Adjudicated			
Torrington	4TH ENL CITY OF TORRINGTON NEW NO. 5	P80868.0W	100	200	Fully Adjudicated			
Torrington	CITY OF TORRINGTON NEW NO. 3	P439.0C	750	161	Fully Adjudicated			
Torrington	CITY OF TORRINGTON NEW NO. 3 WELL	CR UW01/480	750	161	Fully Adjudicated	Alluvium		
Torrington	CITY OF TORRINGTON NEW NO. 4	P868.0W	750	200	Fully Adjudicated	Alluvium		
Torrington	CITY OF TORRINGTON NEW NO. 4 WELL	CR UW01/491	750	200	Fully Adjudicated	Alluvium		
Torrington	CITY OF TORRINGTON NEW NO. 5	P14789.0W	1,300	200	Fully Adjudicated	Terrace		
Torrington	CITY OF TORRINGTON NEW NO. 5 WELL	CR UW02/268	1,300	200	Fully Adjudicated	Terrace		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 3 WELL	CR UW01/485	750	161	Fully Adjudicated	Alluvium		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 3 WELL	CR UW01/483	800	161	Fully Adjudicated	Alluvium		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 4 WELL	CR UW04/331	600	200	Fully Adjudicated	Alluvium		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 4 WELL	CR UW01/500	1,000	200	Fully Adjudicated	Alluvium		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 5 WELL	CR UW07/179	100	200	Fully Adjudicated			
Torrington	ENL. CITY OF TORRINGTON NEW NO. 5 WELL	CR UW08/156	175	200	Fully Adjudicated			
Torrington	ENL. CITY OF TORRINGTON NEW NO. 5 WELL	CR UW07/177	1,000	200	Fully Adjudicated	Alluvium		
Torrington	ENL. CITY OF TORRINGTON NEW NO. 5 WELL	CR UW07/176	100	200	Fully Adjudicated			
Torrington	TORRINGTON #8	P1356.0W	750	100	Fully Adjudicated			
Torrington	TOWN OF TORRINGTON #1	P437.0C	300	90	Fully Adjudicated			
Torrington	TOWN OF TORRINGTON #11	P45138.0W	900	125	Fully Adjudicated	Terrace		
Torrington	TOWN OF TORRINGTON #15	P69070.0W	950	128	Fully Adjudicated	Alluvium		
Torrington	TOWN OF TORRINGTON #2	P438.0C	300	90	Fully Adjudicated			
Torrington	TOWN OF TORRINGTON #6	P757.0W	1,200	132	Fully Adjudicated			
Wheatland	BLACK MOUNTAIN #1	P48832.0W	475	585	Fully Adjudicated			
Wheatland	BLACK MOUNTAIN #2	P55321.0W	300	619	Fully Adjudicated	Dune Sand and Arikaree and White River FmsLoess		
Wheatland	TOWN OF WHEATLAND WELL #7	P36.0W	425	453	Fully Adjudicated			
Wheatland	WHEATLAND #5	P490.0C	550	509	Fully Adjudicated	Dune Sand and Arikaree and White River FmsLoess		
Wheatland	WHEATLAND #6 WELL	P491.0C	475	506	Fully Adjudicated	Dune Sand and Arikaree and White River FmsLoess		
Wheatland	WHEATLAND WELL #8	P2187.0W	450	500	Fully Adjudicated			
Wheatland	WHEATLAND WELL #9	P2188.0W	450	551	Fully Adjudicated			
Totals			58,582					

DOM-Domestic, IND-Industrial, IRR-Irrigation, MIS-Miscellaneous, STK-Stock

As discussed in **Section 5.7.4**, the individual PWS reports provide valuable information on recharge areas, resource vulnerability and local sources of potential contaminants for specific groundwater sources. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming. Additional information on the SWAP in Wyoming can be accessed at:

http://deq.state.wy.us/wqd/www/SWP%20WHP/SWAP%20FAQs.asp.

Table 8-11 provides SEO water right permit number, yield, producing unit and depth data for 343 SWAP wells and 26 springs in the Platte River Basin. The SEO permit numbers, shown, can be correlated with the wells shown in **Tables 8-9 and 8-10**. Although most wells in the SWAP database produce groundwater from alluvial deposits and Tertiary aquifers, many older bedrock aquifers are also identified as producing units in **Table 8-11**.

Figure 8-23 shows the geospatial distribution of SWAP wells in the Platte River Basin and their relative susceptibility to potential contaminants. Insert maps on **Figure 8-23** are scaled to show more detail in areas where the wells are closely spaced.

8.4.4.6 Industrial and mineral use and CBNG permits (Figure 8-24)

Table 8-6 lists 476 SEO permits for industrial (IND) and 110 permits for coalbed methane (CBM) use, and **Table 8-7** lists 3 CDWR permits for industrial (IND) use in the Platte River Basin. Primary industrial uses in the Platte River Basin include conventional oil and gas processing, uranium and coal mining operations, aggregate and gravel mining, cement production, power generation, and roadway and general construction. Groundwater withdrawn for industrial operations is also commonly reused for general industrial purposes such as dust control. The SEO database does not identify specific industrial uses; individual permit summaries must be reviewed for that information. A full review of all permits was beyond the scope of this project.

Figure 8-24 shows the distribution of likely drilled wells permitted for industrial use in the Platte River Basin issued before and after January 2005, along with a general description of the operations supported in specific areas. Most industrial wells in the Platte River Basin are clustered in rural areas around conventional oil and gas fields, mining operations, and population centers.

The depth vs. yield tables on **Figure 8-24** show that most industrial well permits have been issued for depths 100 to 1000 feet, with permitted yields varying over a wide range for both total permits and permits issued since 2005.

Table 8-10 WSEO incomplete, cancelled, abandoned, and not listed well permits in the Wyoming PtRB database by municipal use (p. 328–331).

Municipality or Community	Well Name	WSEO Permit Number	Permit yield (gpm)	Well Depth (feet)	Permit Status	New since 2005	Multiple Use Well	Hydro-geologic unit	Depth of Producing Interval (feet)
Albin	ALBIN 04-01 NOELLE	P165191.0W	100						260-320
Albin	ALBIN 04-02 MARY	P165192.0W	150						
Albin	TOWN OF ALBIN #1	P4059.0W	25	500	Incomplete				
Albin	TOWN OF ALBIN #2	P4060.0W	25	280	Incomplete				
Albin	TOWN OF ALBIN #3	P33728.0W	500		Cancelled				
Albin	TOWN OF ALBIN #4	P33729.0W	500		Cancelled				
Albin	TOWN OF ALBIN #4	P42983.0W	200	245	Incomplete				
Alcova	ALCOVA #5	P32606.0W	300	40					
Alcova	JADE #2	P933.0W	23	600	Cancelled				
Bairoil	ENL BATTLE SPRINGS #1	P71036.0W		2,080	Incomplete		Yes		
Bairoil	ENL BATTLE SPRINGS #2	P71037.0W		2,084	Incomplete		Yes		
Bairoil	ENL BATTLE SPRINGS #3	P71038.0W		2,010	Incomplete		Yes		
Bairoil	ENL BATTLE SPRINGS #4	P71039.0W		2,043	Incomplete		Yes		
Bairoil	ENL BATTLE SPRINGS #6	P71040.0W		2,010	Incomplete		Yes		
Bairoil	ENL BATTLE SPRINGS #8	P71041.0W		2,002	Incomplete		Yes		
Burns	A 4 WATER	CR UW04/356	850						
Burns	A-1 WATER	CR UW03/382	100						
Burns	A-2 WATER WELL	CR UW03/383	275						
Burns	A3 WATER WELL	CR UW03/386	150						
Casper	#2 H R N	P584.0W	4	31					
Casper	AIRPORT #1	P1062.0W	30	3,100			Yes		
Casper	BRYAN #14	P18.0W	500	45	Incomplete				
Casper	CAISSON 4	P103723.0W	4,500		Cancelled				
Casper	CAISSON 5	P103724.0W	4,500		Cancelled				
Casper	CAISSON 6	P103725.0W	4,500		Cancelled				
Casper	CAISSON 7	P103726.0W	4,500		Cancelled				
Casper	CASPAR 19	P103719.0W	1,000		Incomplete				
Casper	CASPAR 20	P103720.0W	1,000		Incomplete				
Casper	CASPAR 21	P103721.0W	1,000		Incomplete				
Casper	CASPAR 22	P103722.0W	1,000	39	Incomplete				
Casper	CASPER #1	P615.0C	500	30	Incomplete				
Casper	CASPER #10	P600.0G	600	28	Incomplete				
Casper	CASPER #14	P601.0G	600	30	Incomplete				
Casper	CASPER #15	P602.0G	800	34	Incomplete				
Casper	CASPER #19	P78168.0W	600		Cancelled				
Casper	CASPER #2	P616.0C	500	30	Incomplete				
Casper	CASPER #20	P78169.0W	600		Cancelled				
Casper	CASPER #21	P78170.0W	600		Cancelled				
Casper	CASPER #3	P617.0C	500	31	Incomplete				
Casper	CASPER #4	P594.0G	700	38	Incomplete				
Casper	CASPER #5	P595.0G	700	34	Incomplete				
Casper	CASPER #6	P596.0G	700	36	Incomplete				
Casper	CASPER #7	P597.0G	700	34	Incomplete				
Casper	CASPER #8	P598.0G	600	32	Incomplete				
Casper	CASPER #9	P599.0G	700	30	Incomplete				
Casper	CITY OF CASPER #11	P49.0W	750	30	Incomplete				
Casper	CITY OF CASPER #12	P50.0W	750	30	Incomplete				
Casper	CITY OF CASPER #16	P1152.0W	600	35	Incomplete				
Casper	CITY OF CASPER #17	P1153.0W	500	41	Incomplete				
Casper	CITY OF CASPER #18	P1154.0W	1,000	43	Incomplete				
Casper	CLARE #11	P17.0W	750	43	Incomplete				
Casper	JADE #1	P1994.0W	75	35					
Casper	JADE #1	P2161.0W	70		Cancelled				
Casper	MORAD #1	P1797.0W	450	42	Incomplete				
Casper	MORAD #2	P1798.0W	700	39	Incomplete				
Casper	MORAD #3	P1799.0W	700	43	Incomplete				
Casper	MORAD 10	P103730.0W	1,000	38	Incomplete				
Casper	MORAD 11	P103731.0W	1,000		Incomplete				
Casper	MORAD 12	P103732.0W	1,000		Incomplete				
Casper	MORAD 13	P103733.0W	1,000	36	Incomplete				
Casper	MORAD 14	P103734.0W	1,000		Cancelled				
Casper	MORAD 15	P103735.0W	1,000		Cancelled				
Casper	MORAD 16	P103736.0W	1,000	42	Incomplete				
Casper	MORAD 17	P103737.0W	1,000	42	Incomplete				
Casper	MORAD 18	P103738.0W	1,000		Cancelled				
Casper	MORAD 19	P103739.0W	1,000		Cancelled				
Casper	MORAD 20	P103740.0W	1,000		Cancelled				
Casper	MORAD 21	P103741.0W	1,000		Cancelled				
Casper	MORAD 22	P103742.0W	1,000		Cancelled				
Casper	MORAD 7	P103727.0W	1,000		Incomplete				
Casper	MORAD 8	P103728.0W	1,000		Incomplete				
Casper	MORAD 9	P103729.0W	1,000	34	Incomplete				
Casper	PARK WELL #1	P574.0W	700	29					
Casper	PARK WELL #2	P575.0W	920	28					
Casper	PARK WELL #3	P576.0W	1,000	33					
Casper	PARK WELL #4	P577.0W	850	32					
Casper	PINEVIEW #1	P133.0W	700		Cancelled		Yes		
Casper	RANNEY #1	P46.0W	1,400	24	Incomplete				
Casper	RANNEY #2	P47.0W	1,100	26	Incomplete				
Casper	RANNEY #3	P48.0W	1,550	25	Incomplete				
Casper	RED BUTTE #4	P934.0W	150		Cancelled				
Casper	RIVER CROSS #1	P91.0W	300		Cancelled				
Casper	RIVERSIDE TERRACE WELL #1	P40.0W	36	27	Incomplete				
Casper	RIVERSIDE TERRACE WELL #2	P78.0W	20	27	Incomplete				
Casper	VOORHIES #12	P16.0W	750	45	Incomplete				
Centennial	CENTENNIAL WELL #1	CR UW09/011	45						
Centennial	CENTENNIAL WELL #2	CR UW09/012	50						
Centennial	ENL CENTENNIAL #2	CR UW09/013	15						
Cheyenne	2ND ENL. BELL # 10	P189078.0W	75		Incomplete	Yes	Yes		
Cheyenne	2ND ENL. BELL NO. 5 WELL	P137038.0W	125		Incomplete		Yes		
Cheyenne	2ND ENL. BORIE No.1 (CHEYENNE No. 56)	CR UW10/456	175						
Cheyenne	BELL #10	CR UW07/128	150						
Cheyenne	BELL #11 WELL	CR UW07/129	800						
Cheyenne	BELL #12	CR UW07/130	300						
Cheyenne	BELL #17	CR UW07/131	300						
Cheyenne	BELL #5	CR UW07/125	200						
Cheyenne	BELL #8 (DEEPENED)	CR UW07/127	225						
Cheyenne	BELL NO. 6	CR UW07/126	350						
Cheyenne	BELVOIR NO. 5	P189075.0W	700		Incomplete	Yes			
Cheyenne	BELVOIR NO. 6	P189077.0W	300		Incomplete	Yes			
Cheyenne	CHEYENNE #1 (SILVER CROWN #1)	P262.0C	275	947	Cancelled				
Cheyenne	CHEYENNE #13 (HOLMAN WELL #1)	CR UW07/098	475						
Cheyenne	CHEYENNE #15 (ELKAR WELL #1)	CR UW07/099	300						
Cheyenne	CHEYENNE #17 (BAILEY #1)	P267.0C	387	180	Cancelled				
Cheyenne	CHEYENNE #2 (SILVER CROWN #2)	P263.0C	275	843	Cancelled				

Table 8-10 WSEO incomplete, cancelled, abandoned, and not listed well permits in the Wyoming PtRB database by municipal use (cont).

Cheyenne	CHEYENNE #20 (BAILEY #5)	CR UW07/100	125				
Cheyenne	CHEYENNE #22 (EDDY #2)	CR UW07/101	250				
Cheyenne	CHEYENNE #25 (KOPPES #1)	CR UW07/102	325				
Cheyenne	CHEYENNE #26 (KOPPES #2)	CR UW07/103	375				
Cheyenne	CHEYENNE #27 (ELKAR #3)	P272.0C	143	369	Abandoned		
Cheyenne	CHEYENNE #28 (HAPPY JACK #1)	P273.0C	250	152	Cancelled		
Cheyenne	CHEYENNE #29 (HAPPY JACK #2)	P274.0C	200	184	Cancelled		
Cheyenne	CHEYENNE #3 (SILVER CROWN #3)	P264.0C	225	850	Cancelled		
Cheyenne	CHEYENNE #30 (HAPPY JACK #3)	CR UW07/104	250				
Cheyenne	CHEYENNE #31 (MERRITT #1)	CR UW07/105	200				
Cheyenne	CHEYENNE #33 (TAX #1)	P277.0C	240	375	Cancelled		
Cheyenne	CHEYENNE #36 (MERRITT #5)	CR UW07/106	200				
Cheyenne	CHEYENNE #37 (MERRITT #6)	CR UW07/107	150				
Cheyenne	CHEYENNE #41 (KOPPES #3)	CR UW07/108	325				
Cheyenne	CHEYENNE #44 (ELKAR #5)	CR UW07/110	500				
Cheyenne	CHEYENNE #47 (KING #1)	P283.0C	480	200			
Cheyenne	CHEYENNE #48 (KING #2)	CR UW08/282	150				
Cheyenne	CHEYENNE #50 (ELKAR WELL #7)	CR UW07/111	375				
Cheyenne	CHEYENNE #51 (FINNERTY #2)	CR UW07/112	350				
Cheyenne	CHEYENNE #52 (KING #4)	CR UW07/113	250				
Cheyenne	CHEYENNE #53 (KOPPES #5)	P288.0C	450	230	Abandoned		
Cheyenne	CHEYENNE #54 (KING #5)	CR UW07/114	275				
Cheyenne	CHEYENNE #55 (KOPPES WELL #6)	CR UW07/115	200				
Cheyenne	CHEYENNE #56 (BORIE #1)	CR UW07/116	300				
Cheyenne	CHEYENNE #57 (WEBER #1)	CR UW07/117	550				
Cheyenne	CHEYENNE #58 (CONREY #1)	CR UW07/118	225				
Cheyenne	CHEYENNE No.47 (KING No. 1)	CR UW10/450	275				
Cheyenne	ENL BELL #5	CR UW07/135	100				
Cheyenne	Enl Bell #8	P111936.0W	175	170	Incomplete		
Cheyenne	ENL BORIE #1 (CHEYENNE #56)	CR UW10/455	600				
Cheyenne	ENL CHEYENNE #44 (ELKAR #5)	CR UW07/137	250				
Cheyenne	ENL EDDY #2 (CHEYENNE #22)	CR UW10/451	100				
Cheyenne	ENL ELKAR No. 7 (CHEYENNE No. 50)	CR UW10/453	325				
Cheyenne	ENL KING #4 (CHEYENNE #52)	CR UW10/454	250				
Cheyenne	Enl Koppes #2	P111935.0W	350	331	Incomplete		
Cheyenne	ENL Koppes #3	P121582.0W	100	392	Incomplete		
Cheyenne	ENL KOPPES N0. 1 (CHEYENNE No. 25)	CR UW10/452	175				
Cheyenne	ENL MERRITT #14	CR UW07/136	100				
Cheyenne	ENL. BELL NO. 10	P172981.0W		250		Yes	Yes
Cheyenne	ENL. CHEYENNE NO. 51 (FINNERTY NO. 2)	P172980.0W		210		Yes	
Cheyenne	Enlarged Koppes No. 2 Well	CR UW15/050	275				
Cheyenne	FREED WELL #1	P330.0W	100	306	Cancelled		
Cheyenne	LONE TREE #2	P189076.0W	500		Incomplete	Yes	
Cheyenne	MERRITT #14	CR UW07/124	150				
Cheyenne	MERRITT #15 WELL	CR UW07/120	350				
Cheyenne	MERRITT #5 WELL,, Enl.	CR UW08/287	150				
Cheyenne	MERRITT #8	CR UW07/119	325				
Cheyenne	MERRITT #9 WELL	CR UW07/123	320				
Cheyenne	NORTH BELL WELL FIELD #16	CR UW07/132	500				
Cheyenne	NORTH BELL WELL FIELD #24	CR UW07/133	300				
Cheyenne	NORTH BELL WELL FIELD #25	CR UW07/134	425				
Cheyenne	ORCHARD VALLEY #1	P151.0C	350	240	Incomplete		Yes
Cheyenne	ORCHARD VALLEY #2	P152.0C	150	240	Incomplete		
Cheyenne	ROSENBLUM #2	P524.0W	125	485	Cancelled		
Cheyenne	SCHOOL #1	CR UW07/121	225				
Cheyenne	SCHOOL #2	CR UW07/122	425				
Cheyenne	SOUTH CHEYENNE #1	P1580.0W	500		Cancelled		
Cheyenne	SOUTH CHEYENNE #2	P2023.0W	500		Cancelled		
Cheyenne	STATE #1	P43985.0W	100	297	Cancelled		
Cheyenne	STATE #2	P43986.0W	400	351	Cancelled		
Cheyenne	TAX #2	P73611.0W	150	310	Abandoned		
Cheyenne	URBAN DEVELOPMENT WELL #1	P756.0W	24	420			
Cheyenne	WALBACH #1	P95387.0W	500		Cancelled		Yes
Cheyenne	WEBER #1	P43987.0W	300	270	Cancelled		
Chugwater	#1	P1393.0W	30	80			
Chugwater	#2	P1394.0W	60	80			
Chugwater	#3	P1395.0W	90	128	Incomplete		
Chugwater	CHUGWATER #5	P154780.0W	300				
Chugwater	Chugwater Well #4	P119526.0W	300	120	Incomplete		
Douglas	BOX ELDER WELL NO. 1	P148646.0W	30	1,170	Cancelled		
Douglas	SHEEP MOUNTAIN WELL #1	P97415.0W	910	1,165	Incomplete		Yes
Elk Mountain	ELK MOUNTAIN #1 (#1UPRR-IRENE)	P1529.0W	63	3,200			
Elk Mountain		CR UW11/282	130				
Elk Mountain		CR UW11/283	130				
Encampment	ENCAMPMENT #3	P65772.0W	100		Cancelled		
Evansville	EVANSVILLE #6	P585.0W	250	37			
Evansville	EVANSVILLE #7	P27032.0W	600		Cancelled		
Fort Laramie	ENL FORT LARAMIE #2	CR UW01/058	300				
Fort Laramie	ENL FORT LARAMIE #2	P9902.0W	300	82	Cancelled		
Fort Laramie	FORT LARAMIE #2	CR UW01/057	500				
Fort Laramie	FORT LARAMIE #3	P62637.0W	2	95	Incomplete		
Fort Laramie	FT. LARAMIE #1 WELL	CR UW01/056	825				
Glendo	DOWNEY WELL #1	P433.0C	225	410	Incomplete		
Glendo	ENL. ROBBENS WELL	P191656.0W	45		Unadjudicated	Yes	
Glendo	GLENDO #1	P5363.0W	120		Cancelled		
Glendo	ROBBENS WELL	P175017.0W	30	650		Yes	
Glendo	THOMAS MEMORIAL WELL NO. 1	P191563.0W	200		Incomplete	Yes	
Glendo	TOWN WELL NO. 1	P168631.0W	500			Yes	
Glendo	WELL #4	P2183.0W	200		Cancelled		
Glenrock	FOX HILLS #2	P44855.0W	240	706	Incomplete		
Glenrock	GLENROCK WELL NO. 5	P131362.0W		1,174	Complete		Yes
Glenrock	GLENROCK #1	P17439.0W	150	35	Incomplete		
Glenrock	GLENROCK #2	P17440.0W	120	35	Incomplete		
Glenrock	GLENROCK #3	P17441.0W	70	33	Incomplete		
Glenrock	GLENROCK #4	P17442.0W	80	31	Incomplete		
Glenrock	GLENROCK WELL NO. 7	P189662.0W	1,500		Incomplete	Yes	
Glenrock	GLENROCK-ABERNATHY #1	P278.0W	500		Cancelled		
Glenrock	LITTLE DEER CREEK #1	P68630.0W	1,100	260	Incomplete		
Glenrock	LITTLE DEER CREEK #2	P71254.0W	650	250	Incomplete		
Glenrock	LYTHGOE WELL	P67329.0W		350	Abandoned		
Glenrock	PARK WELL	P67328.0W	360	425			
Guernsey	GUERNSEY #3	P61817.0W	700	91			
Guernsey	GUERNSEY #4	P106505.0W	1,000	188	Cancelled		
Guernsey	TOWN OF GUERNSEY WELL #1	P1562.0W	600	188	Incomplete		
Hanna	EMS 1	P74484.0W	1,200	184	Incomplete		
Hanna	EMS 2	P74485.0W	1,200		Cancelled		
Hanna	HANNA #1	P46207.0W	1,000		Cancelled		
Hanna	HANNA #1	P55253.0W	1,000		Cancelled		Yes
Happy Jack	HAPPY JACK III	P69749.0W	650		Cancelled		
Hartville	HARTVILLE #1	P33900.0W	50	200			Yes
Hartville	HARTVILLE #2	P363.0G	60	8	Incomplete		Yes

Table 8-10 WSEO incomplete, cancelled, abandoned, and not listed well permits in the Wyoming PtRB database by municipal use (cont).

Hartville	TOWN OF HARTVILLE #3 HEW	P44218.0W	150		Cancelled		
Hartville	TOWN OF HARTVILLE #3 WELL	P39165.0W		426	Abandoned		
Hartville	TOWN OF HARTVILLE #4 HEW	P44217.0W	150		Cancelled		
Hartville	TOWN OF HARTVILLE #5 HEW	P44216.0W		150	Abandoned		
Hartville	TOWN OF HARTVILLE #6 HEW	P43884.0W	100		Cancelled		
Hartville	TOWN OF HARTVILLE #7 KELLYS PARK	P44468.0W	300		Cancelled		
Hartville	TOWN OF HARTVILLE #7 KELLYS PARK	P56437.0W	250	61	Incomplete		Yes
Hartville	TOWN OF HARTVILLE #8 KELLYS PARK	P71532.0W	270	63	Incomplete		
Jeffry City	JEFFREY CITY TOWNSITE #1	P52.0W	175	152	Incomplete		
Jeffry City	JEFFREY CITY TOWNSITE #3	P31835.0W	500	241	Incomplete		
Jeffry City	JEFFREY CITY TOWNSITE #4	P43808.0W	50	300	Incomplete		
Jeffry City	SPLIT ROCK TOWNSITE #1	P541.0G	80	90	Incomplete		
LaGrange	ENL LAGRANGE #1	P50412.0W	400	100	Cancelled		
LaGrange	ENL LAGRANGE #2	CR UW05/226	125				Yes
LaGrange	ENL WENDT	CR UW02/107					
LaGrange	LAGRANGE #1	CR UW04/111	450				Yes
LaGrange	LAGRANGE #2	CR UW05/223	450				Yes
Laramie	ENL POPE #4 WELL	CR UW08/305	50				
Laramie	ENL POPE #2	CR UW08/303	75				
Laramie	ENL POPE #3	CR UW08/293	250				
Laramie	ENL POPE #3	CR UW08/304	50				
Laramie	ENL POPE #3	P45894.0W	610		Cancelled		
Laramie	ENL TURNER #1	CR UW08/298	800				
Laramie	ENL TURNER #1	CR UW08/302	300				
Laramie	ENL TURNER #2	CR UW08/297	200				
Laramie	POPE #1	CR UW08/288	550				
Laramie	POPE #2	CR UW08/289	600				
Laramie	POPE #3	CR UW08/291	600				
Laramie	POPE #4	CR UW08/294	1,750				
Laramie	POPE #4	P45895.0W	1,800		Cancelled		
Laramie	POPE #5	P45896.0W	2,000		Cancelled		
Laramie	POPE #6	P45897.0W	2,000		Cancelled		
Laramie	POPE #7	P45898.0W	2,000		Cancelled		
Laramie	SIMPSON NO. 1	P192087.0W	1,500		Incomplete		Yes
Laramie	SIMPSON NO. 2	P192088.0W	1,500		Incomplete		Yes
Laramie	SIMPSON NO. 3	P192089.0W	1,500		Incomplete		Yes
Laramie	SOLDIER SPRINGS #2	P45893.0W	2,000		Cancelled		
Laramie	SPUR #1	P45899.0W	2,000		Cancelled		
Laramie	SPUR #2	P106548.0W	2,500		Cancelled		
Laramie	SPUR #2	P45900.0W	2,000		Cancelled		
Laramie	SPUR #3	P45901.0W	2,000		Cancelled		
Laramie	TURNER #1	CR UW08/295	1,400				
Laramie	TURNER #1	P156.0C	600	236	Cancelled		
Laramie	TURNER #1	P38448.0W	900	551	Cancelled		
Laramie	TURNER #1	P45891.0W	1,400		Cancelled		
Laramie	TURNER #2	CR UW08/296	1,400				
Laramie	TURNER #2	P157.0C	520	557	Cancelled		
Laramie	TURNER #2	P45892.0W	1,400		Cancelled		
Laramie	TURNER #3	P158.0C		246	Cancelled		
Laramie	WEST SIMPSON NO. 1	P192090.0W	2,500		Incomplete		Yes
Laramie		CR UW11/072	1,675				
Laramie		CR UW11/075	1,535				
Lingle	ENL WELL #6	CR UW06/224	600				
Lingle	LINGLE #4	CR UW01/086	600				
Lingle	LINGLE #5	CR UW01/087	475				
Lingle	WELL #6	CR UW06/223	500				
Medicine Bow	COMO #4	CR UW07/172	600				
Medicine Bow	COMO WELL #3	P40066.0W	600	299	Abandoned		
Medicine Bow	COMO WELLS	CR UW07/171	139				
Medicine Bow	ENL COMO WELLS	CR UW07/174	211				
Medicine Bow	FIRST ENL. COMO WELL #3	P44465.0W	400				
Mills	ENL. MILLS NO. 9	P180212.0W	115	35	Complete	Yes	
Mills	MILLS #1	CR UW09/087	300				
Mills	MILLS #2	CR UW09/088	300				
Mills	MILLS #2,, Enl.	CR UW09/096	100				
Mills	MILLS #3	CR UW09/089	600				
Mills	MILLS WELL #4	P2722.0W	600	31	Abandoned		
Mills	MILLS WELL #5	CR UW09/090	600				
Mills	MILLS WELL #6	CR UW09/091	450				
Mills	MILLS WELL #6	P39021.0W	600		Cancelled		
Mills	Mills Well No. 8	CR UW14/046	275				
Mills	MILLS WELL NO. 8	P153070.0W	325	35			
Mills	Mills Well No. 9	CR UW14/047	160				
Mills	MILLS WELL NO. 9	P153071.0W	160	35	Complete		
Mills	Mills Well No. 9,, Enl.	CR UW14/048	115			Yes	
Pine Bluffs	Ekxstrom No. 1 Well,, Enl.	CR UW14/023	750				
Pine Bluffs	ENL EKXSTROM #1 WELL	P37951.0W	750	98	Incomplete		
Pine Bluffs	ENL OF THE PINE BLUFFS MUNICIPAL WELL	CR UW01/245	375				
Pine Bluffs	ENL. PINE BLUFFS NO. SEVEN (7) WELL	P152302.0W	400				
Pine Bluffs	PINE BLUFFS #2 WELL	CR UW01/221	325				
Pine Bluffs	PINE BLUFFS #7	CR UW01/403	750				
Pine Bluffs	PINE BLUFFS #9	P194980.0W	300		Incomplete	Yes	
Pine Bluffs	PINE BLUFFS LANCE/FOX HILLS #1	P178337.0W	250			Yes	
Pine Bluffs	PINE BLUFFS MUNICIPAL	CR UW01/199	375				
Pine Bluffs	Pine Bluffs No. Seven (7) Well,, Enl.	CR UW14/027	250				
Rawlins	CITY OF RAWLINS #2 WELL	P306.0G	120	1,000	Incomplete		Yes
Rawlins	ENL RAWLINS NUGGET WELL #2	P72687.0W	500	1,743			
Rawlins	ENL RAWLINS NUGGET WELL #3	P72688.0W	400	1,625	Incomplete		
Rawlins	NEW CITY #1A	P26777.0W	2	305	Incomplete		
Rawlins	OLD CITY #1	P26776.0W	2	650	Incomplete		
Rawlins	RAWLINS NUGGET WELL #1	P70332.0W	350	1,730	Incomplete		
Rawlins	RAWLINS NUGGET WELL #2	P70333.0W	500	1,743	Incomplete		
Rawlins	RAWLINS NUGGET WELL #3	P70334.0W	500	1,625	Incomplete		
Rawlins	TIGRESS 1 11 A	P79438.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 1 11 B	P79439.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 1 12 A	P79440.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 1 12 B	P79441.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 2 41 A	P79442.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 21 44A	P79443.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 24A	P79444.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 32A	P79445.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 32B	P79446.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 33A	P79450.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 34A	P79449.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 42A	P79447.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 42B	P79448.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 43A	P79451.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 43B	P79452.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 43C	P79453.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 44A	P79454.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 35 44C	P79455.0W	2,000		Cancelled		Yes

Table 8-10 WSEO incomplete, cancelled, abandoned, and not listed well permits in the Wyoming PtRB database by municipal use (cont).

Rawlins	TIGRESS 35 44D	P79456.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 12A	P79457.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 13A	P79459.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 13C	P79460.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 14	P79461.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 14C	P79462.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 14D	P79463.0W	2,000		Cancelled		Yes
Rawlins	TIGRESS 36 33A	P79458.0W	2,000		Cancelled		Yes
Riverside	RIVERSIDE #1	P5216.0W	750		Cancelled		
Riverside	RIVERSIDE #3 (PUMP WELL)	P61403.0W	100		Cancelled		
Riverside	WWDC - RIVERSIDE #4	P83219.0W	100	215	Incomplete		
Riverside	WWDC - RIVERSIDE #5	P85901.0W	1,000				
Riverside	WWDC - RIVERSIDE #6	P85902.0W	165	622	Incomplete		
Riverside	WWDC Riverside No. 4 Well	CR UW14/149	100				Yes
Riverside	WWDC Riverside No. 6 Well	CR UW14/150	165				Yes
Riverside	WWDC-RIVERSIDE #2	P82821.0W	1,000		Cancelled		
Rolling Hills	Rolling Hills #1 Well	P125023.0W	50	1,000	Incomplete		
Rolling Hills	Rolling Hills #2 Well	P125024.0W	50	1,853	Incomplete		
Rolling Hills	ROLLING HILLS #4	P70662.0W	75	1,540	Unadjudicated		
Rolling Hills	ROLLING HILLS #5	P81833.0W	75	1,763	Incomplete		
Rolling Hills	Rolling Hills #6 Well	P125025.0W	80	1,786	Incomplete		
Saratoga	SARATOGA WELL #1	P183913.0W	400			Yes	
Saratoga	SARATOGA WELL #2	P183914.0W	400			Yes	
Saratoga	SARATOGA WELL #3	P183915.0W	400			Yes	
Saratoga	SARATOGA WELL #4	P183916.0W	400			Yes	
Saratoga	SARATOGA WELL #5	P183917.0W	400			Yes	
Shirley Basin	SHIRLEY BASIN WELL #1	CR UW02/258	225				
Shirley Basin	SHIRLEY BASIN WELL #2	CR UW03/436	225				
Torrington	ENL TOWN OF TORRINGTON #15	P118035.0W	350	128	Incomplete		
Torrington	INDUSTRIAL PARK WELL #1	P81751.0W	1,000	80	Incomplete		Yes
Torrington	TORRINGTON #8	CR UW01/493	750				
Torrington	TOWN OF TORRINGTON #1	CR UW01/478	300				
Torrington	TOWN OF TORRINGTON #10	P6476.0W	750		Cancelled		
Torrington	TOWN OF TORRINGTON #11	CR UW04/330	900				
Torrington	TOWN OF TORRINGTON #11	P14330.0W	1,000		Cancelled		
Torrington	TOWN OF TORRINGTON #12	P14331.0W	1,000		Cancelled		
Torrington	TOWN OF TORRINGTON #15	CR UW07/178	950				
Torrington	TOWN OF TORRINGTON #2	CR UW01/479	300				
Torrington	TOWN OF TORRINGTON #6	CR UW01/490	1,200				
Wheatland	BLACK MOUNTAIN #1	CR UW04/394	475				
Wheatland	BLACK MOUNTAIN #2	CR UW04/395	300				
Wheatland	BLACK MOUNTAIN NO. 3	P132328.0W	600				
Wheatland	NORTH PARK #1	P45407.0W	1,500		Cancelled		
Wheatland	NORTH PARK #2	P45408.0W	1,500		Cancelled		
Wheatland	TOWN OF WHEATLAND WELL #7	CR UW04/390	425				
Wheatland	TOWN WELL #1	P107.0C	125	400	Cancelled		
Wheatland	TOWN WELL #2	P108.0C	125	450	Cancelled		
Wheatland	TOWN WELL #3	P109.0C	600	560	Incomplete		
Wheatland	TOWN WELL #4	P110.0C	500	355	Cancelled		
Wheatland	WHEATLAND #5	CR UW04/389	550				
Wheatland	WHEATLAND #6 WELL	CR UW04/388	475				
Wheatland	WHEATLAND WELL #8	CR UW04/391	450				
Wheatland	WHEATLAND WELL #9	CR UW04/392	450				
Yoder	#10	P75167.0W	125		Cancelled		
Yoder	JOHNSON WELL	P64677.0W	18	90			
Yoder	PRODUCTION WELL #1	P94572.0W	25	185	Incomplete		Yes
Yoder	PRODUCTION WELL #2	P81444.0W	40	195	Incomplete		
Yoder	PRODUCTION WELL #3	P94573.0W	12	193	Incomplete		Yes
Yoder	SPIRIT OF 76	P33229.0W	20	115			
Yoder	STATE #04	P138952.0W	45		Cancelled		
Yoder	STATE #04	P149395.0W	45		Cancelled		
Yoder	STATE #04	P168428.0W	45			Yes	
Yoder	TOWER WELL	P64678.0W	16	85			
Yoder	TOWN OF YODER #7	P41349.0W	17	105	Cancelled		
Yoder	WEST 3RD AVE. WELL #1	P26182.0W		96	Abandoned		
Yoder	YODER #5 (PUMP WELL)	P62045.0W			Cancelled		
Yoder	YODER #8	P64676.0W	12	420	Incomplete		
Yoder	YODER #9	P64679.0W	40	100	Cancelled		
Yoder	YODER #9	P69496.0W	70	100			
Yoder	YODER WATER STATION	P69497.0W	18	350			
Totals			244,674				

DOM-Domestic, IND-Industrial, IRR-Irrigation, MIS-Miscellaneous, STK-Stock

8.4.4.6.1 Groundwater use for oil and gas production

Groundwater associated with oil and gas production includes "produced water" withdrawn as a byproduct of oil and gas extraction from hydrocarbon reservoirs, and water utilized in the production and refining of petroleum resources. In some cases, produced water is used in production and refining operations, in others, water for operations is obtained from surface or underground sources. Some water plans (e.g. the 2012 Wind/Bighorn River Basin Water Plan) have treated produced water withdrawals as industrial groundwater use, and others (e.g. the 2006 Platte River basin water plan) have included only water used for production and refining operations in estimates of industrial use. This study presents estimates both for groundwater volumes used for production and refining, and for produced water **(Tables 8-1b and 8-2d)**. Information on groundwater withdrawn for production and refining was derived from the 2007 Statewide and 2006 Platte River Basin Water Plan and associated documents (WWC Engineering, Inc., and others, 2007; Wyoming Water Development Office, 2007; Trihydro Corporation, and others, 2006b; Trihydro Corporation, 2005d). Information on produced water associated with conventional oil and gas operations was obtained from the WOGCC website: http://wogcc.state.wy.us/.

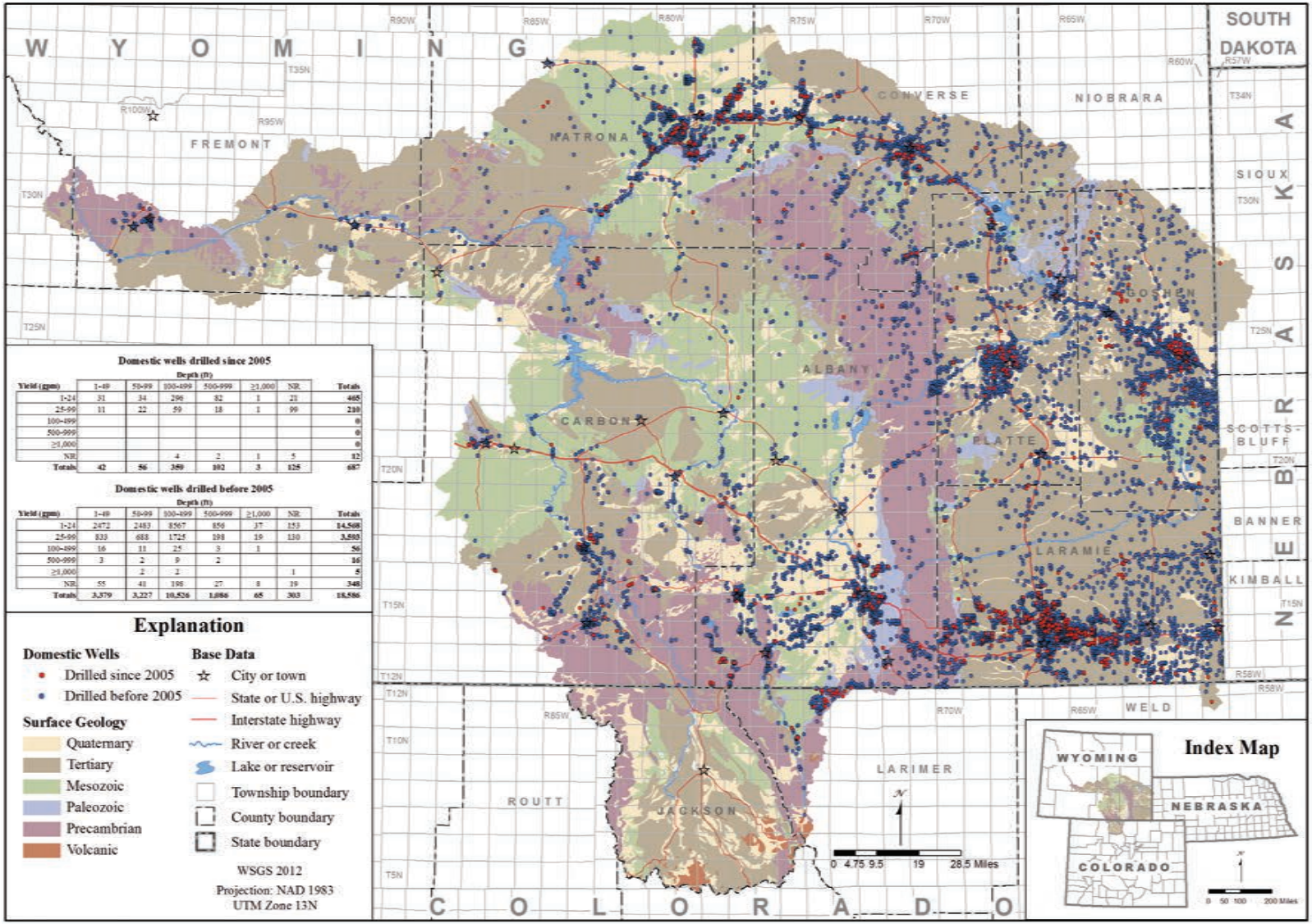
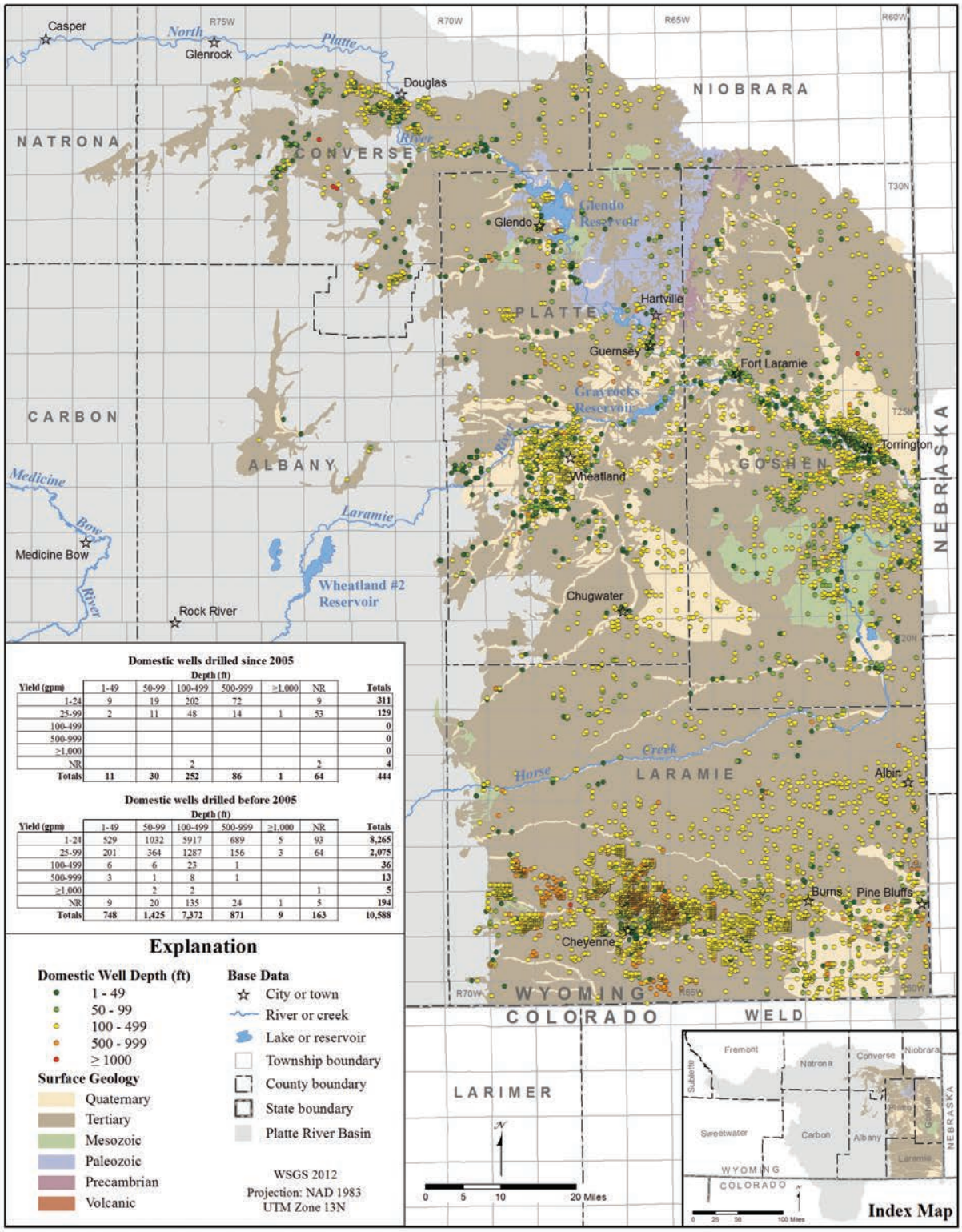


Figure 8-15. Wyoming SEO, Colorado DWR, and Nebraska DNR permitted and drilled domestic wells.



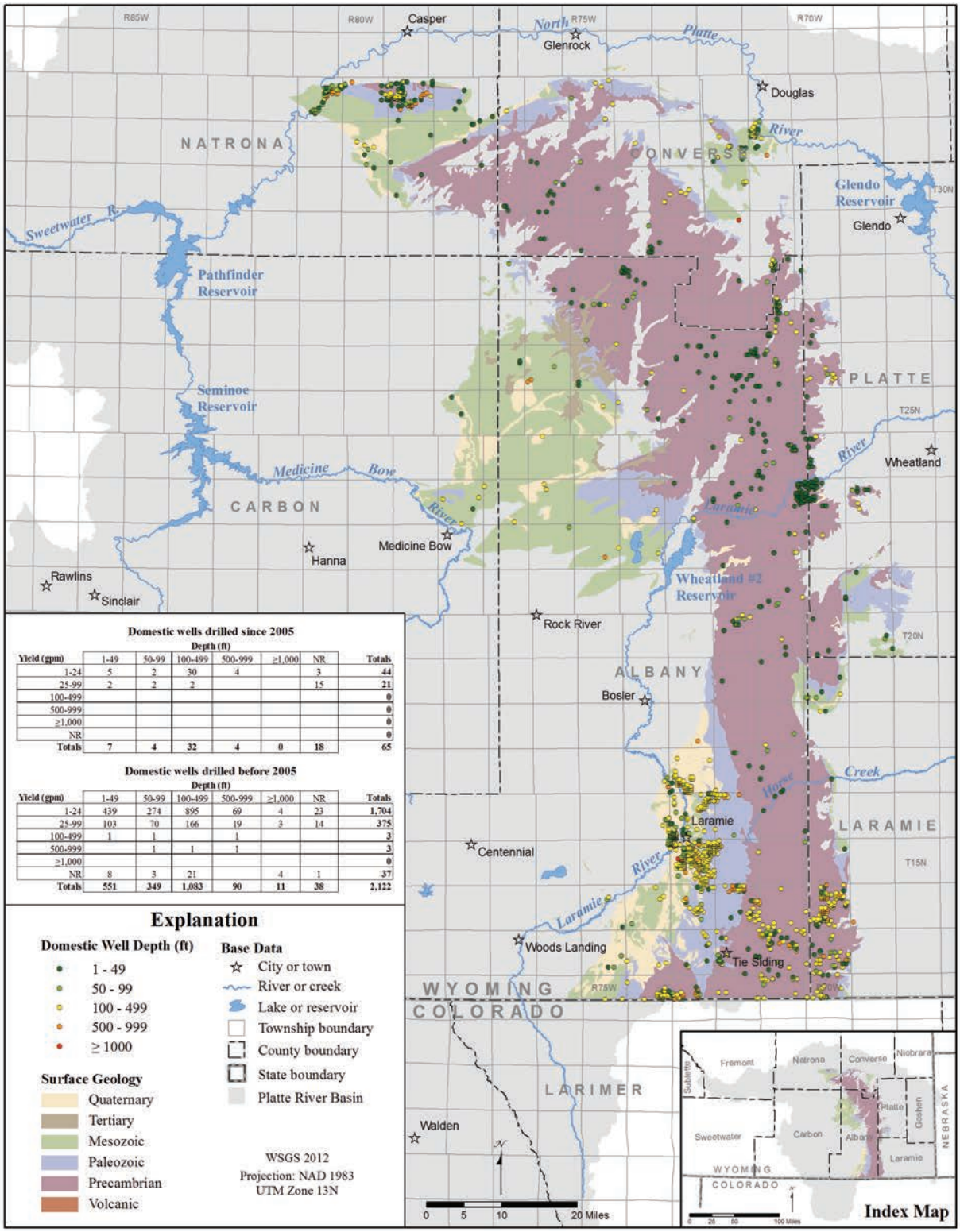
Domestic wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	9	19	202	72		9	**311**
25-99	2	11	48	14	1	53	**129**
100-499							**0**
500-999							**0**
≥1,000							**0**
NR			2			2	**4**
Totals	**11**	**30**	**252**	**86**	**1**	**64**	**444**

Domestic wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	529	1032	5917	689	5	93	**8,265**
25-99	201	364	1287	156	3	64	**2,075**
100-499	6	6	23	1			**36**
500-999	3	1	8	1			**13**
≥1,000		2	2			1	**5**
NR	9	20	135	24	1	5	**194**
Totals	**748**	**1,425**	**7,372**	**871**	**9**	**163**	**10,588**

Figure 8-16. Wyoming SEO permitted and drilled domestic wells in the Denver Basin and Hartville Uplift Subregion.



Domestic wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	5	2	30	4		3	44
25-99	2	2	2			15	21
100-499							0
500-999							0
≥1,000							0
NR							0
Totals	**7**	**4**	**32**	**4**	**0**	**18**	**65**

Domestic wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	439	274	895	69	4	23	1,704
25-99	103	70	166	19	3	14	375
100-499	1	1		1			3
500-999		1	1	1			3
≥1,000							0
NR	8	3	21		4	1	37
Totals	**551**	**349**	**1,083**	**90**	**11**	**38**	**2,122**

Figure 8-17. Wyoming SEO permitted and drilled domestic wells in the Laramie Mountains and Central Uplifts Subregion.

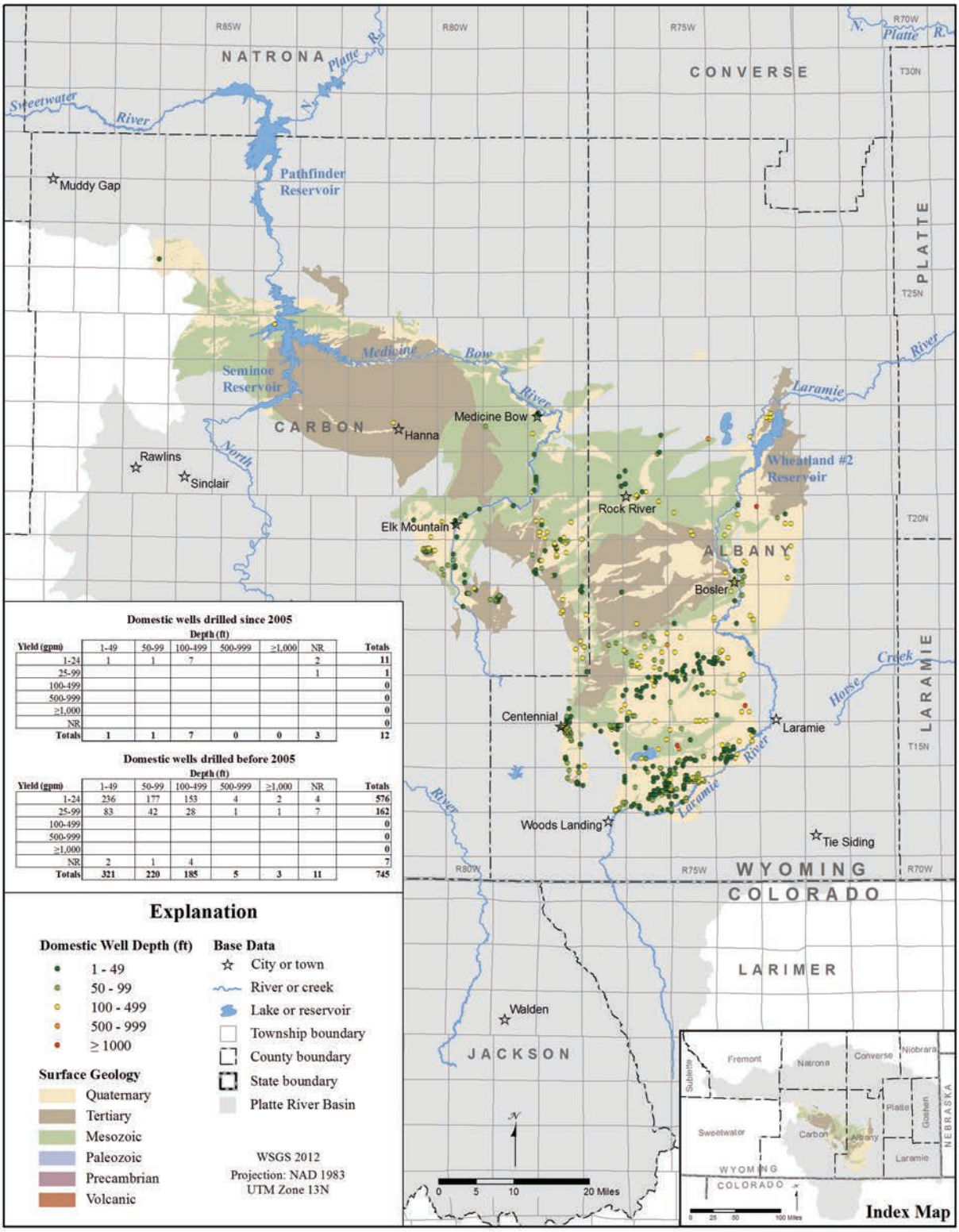
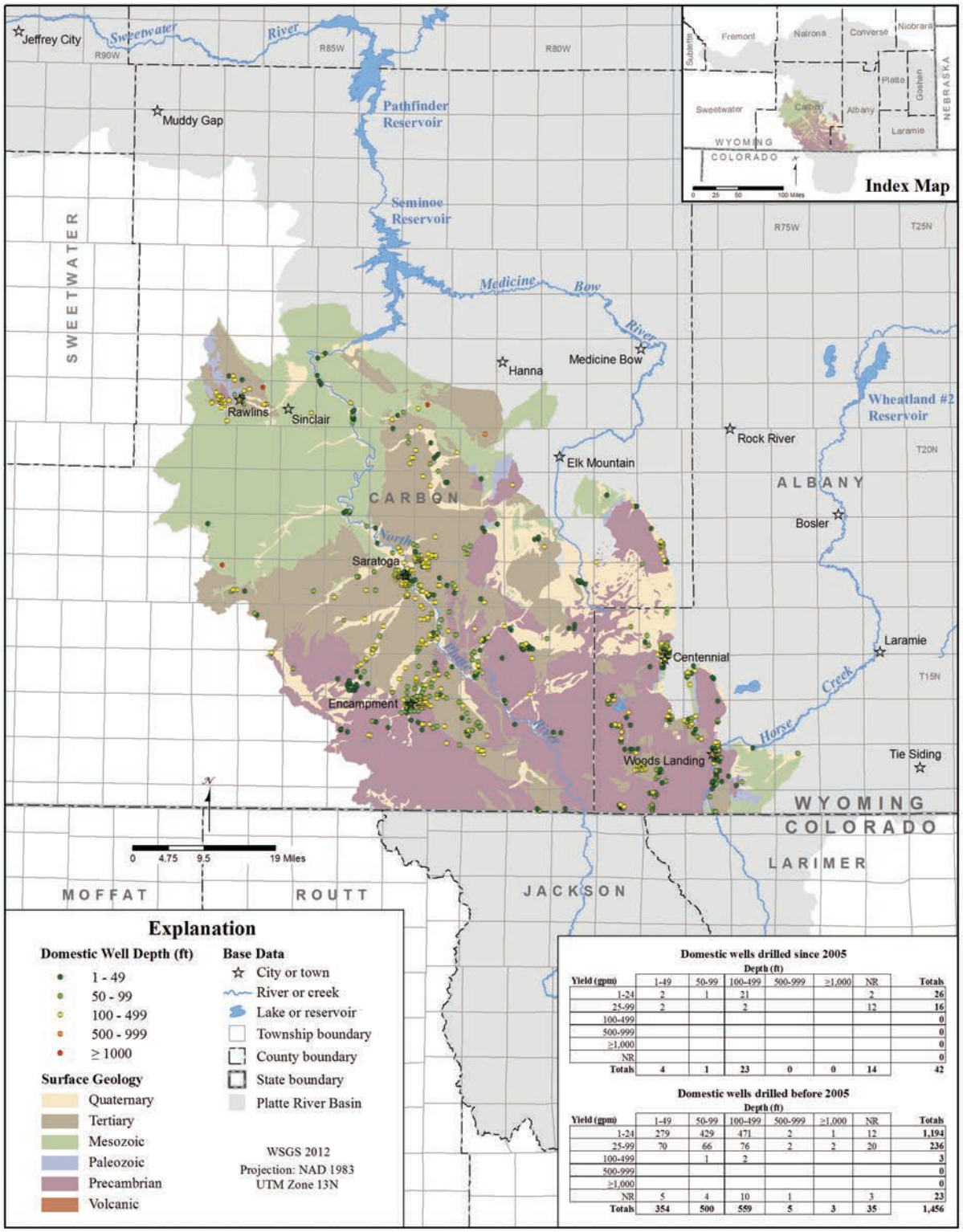


Figure 8-18. Wyoming SEO permitted and drilled domestic wells in the Laramie and Hanna Basins Subregion.



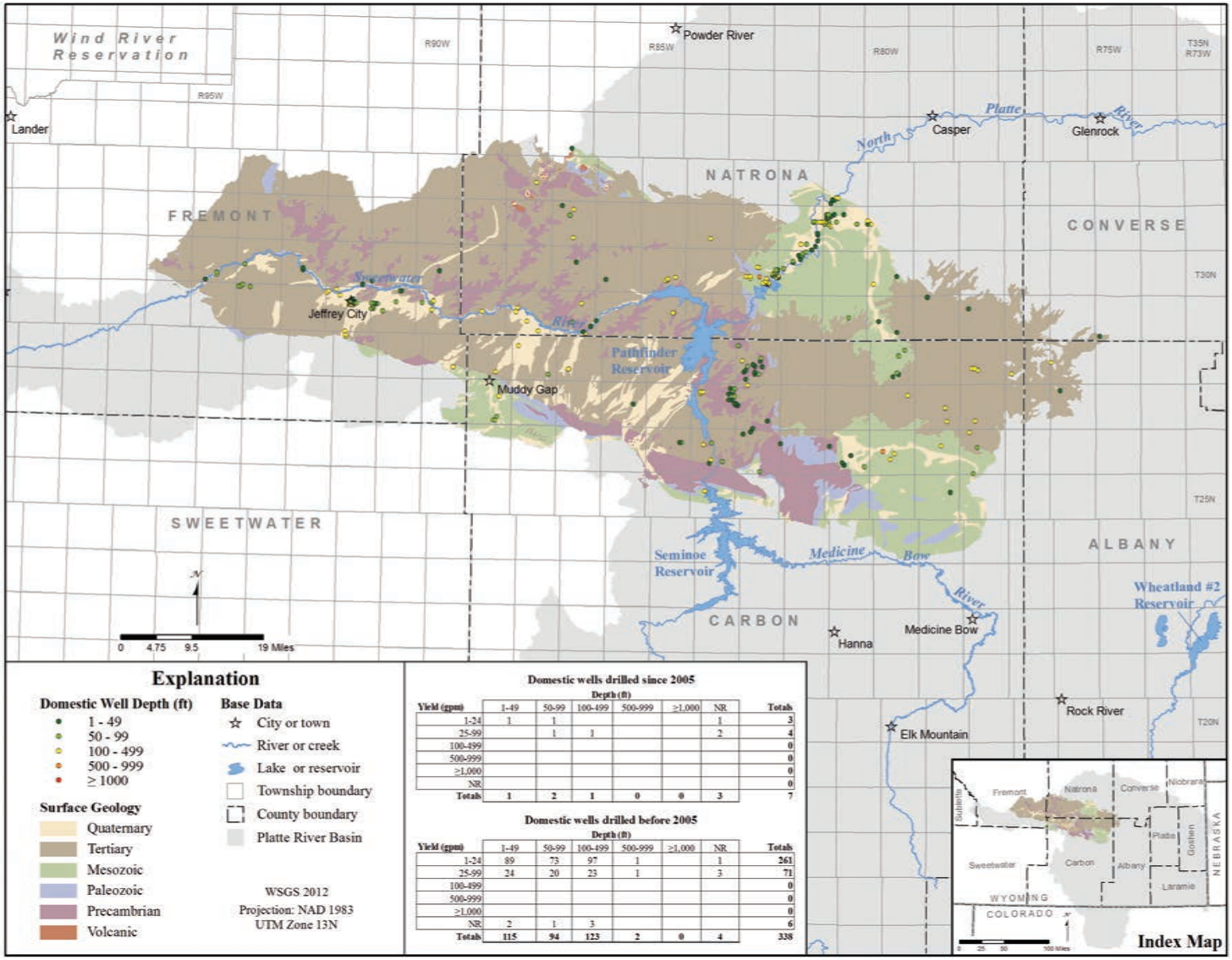
Domestic wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	2	1	21			2	26
25-99	2		2			12	16
100-499							0
500-999							0
≥1,000							0
NR							0
Totals	4	1	23	0	0	14	42

Domestic wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	279	429	471	2	1	12	1,194
25-99	70	66	76	2	2	20	236
100-499		1	2				3
500-999							0
≥1,000							0
NR	5	4	10	1		3	23
Totals	354	500	559	5	3	35	1,456

Figure 8-19. Wyoming SEO permitted and drilled domestic wells in the Medicine Bow Mountains and Sierra Madre Subregion.



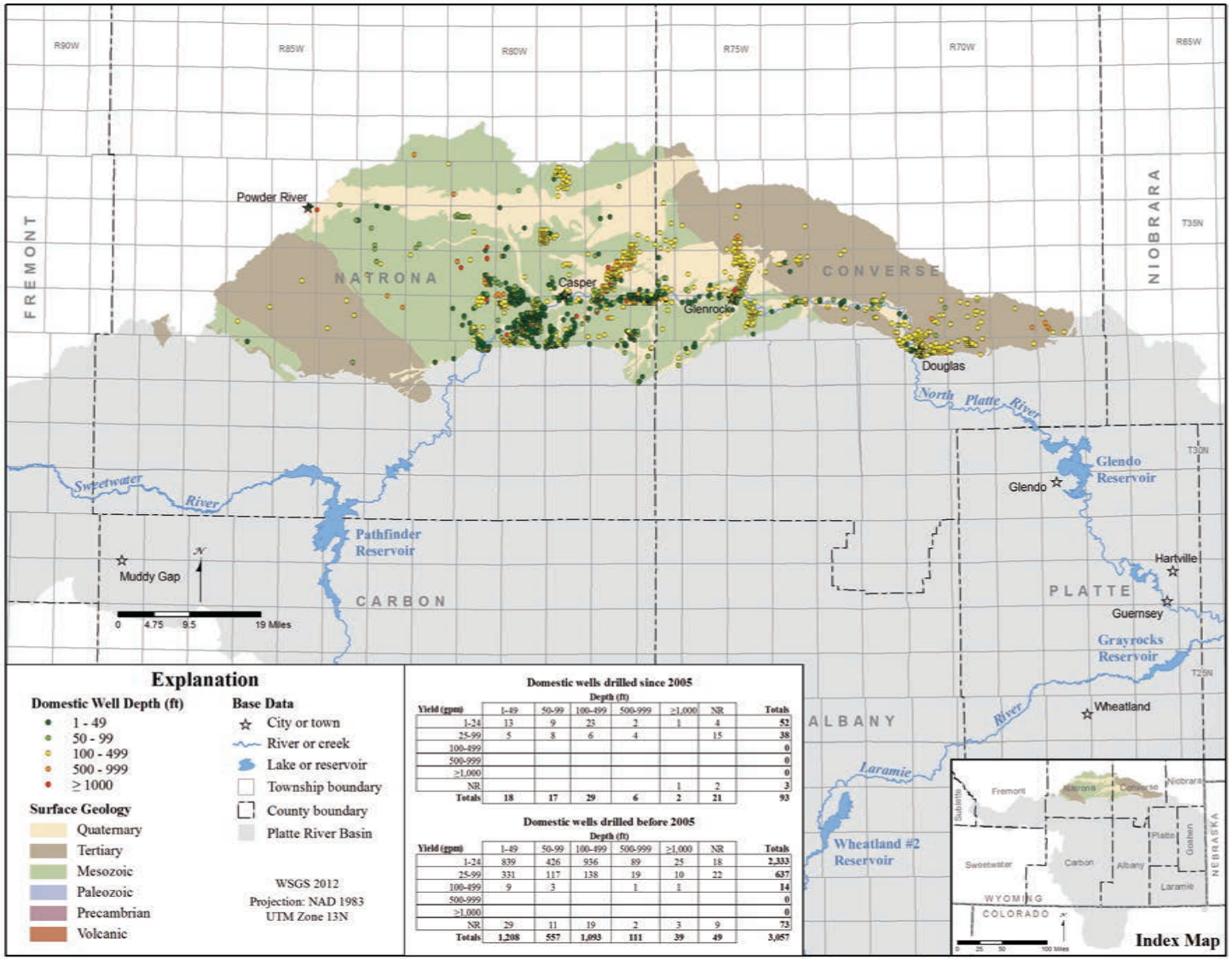
Domestic wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1	1				1	3
25-99		1	1			2	4
100-499							0
500-999							0
≥1,000							0
NR							0
Totals	**1**	**2**	**1**	**0**	**0**	**3**	7

Domestic wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	89	73	97	1		1	261
25-99	24	20	23	1		3	71
100-499							0
500-999							0
≥1,000							0
NR	2	1	3				6
Totals	**115**	**94**	**123**	**2**	**0**	**4**	338

Figure 8-20. Wyoming SEO permitted and drilled domestic wells in the Granite Mountains and Shirley Basin Subregion.



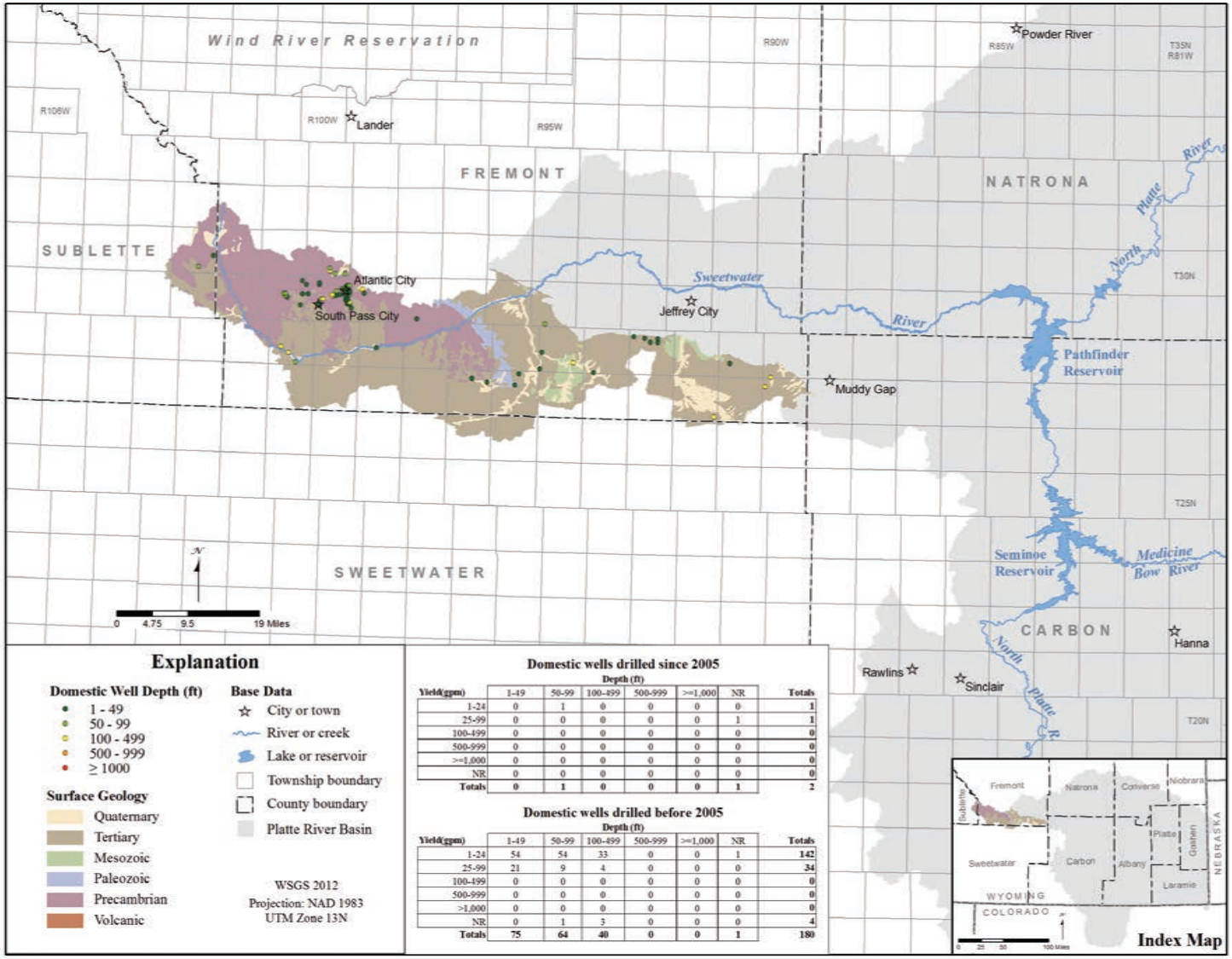
Domestic wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	13	9	23	2	1	4	52
25-99	5	8	6	4		15	38
100-499							0
500-999							0
>1,000							0
NR					1	2	3
Totals	18	17	29	6	2	21	93

Domestic wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	839	426	936	89	25	18	2,333
25-99	331	117	138	19	10	22	637
100-499	9	3		1	1		14
500-999							0
>1,000							0
NR	29	11	19	2	3	9	73
Totals	1,208	557	1,093	111	39	49	3,057

Figure 8-21. Wyoming SEO permitted and drilled domestic wells in the Casper Arch, Wind River and Powder River Basins Subregion.



Yield(gpm)	1-49	50-99	100-499	500-999	>=1,000	NR	Totals
1-24	0	1	0	0	0	0	1
25-99	0	0	0	0	0	1	1
100-499	0	0	0	0	0	0	0
500-999	0	0	0	0	0	0	0
>=1,000	0	0	0	0	0	0	0
NR	0	0	0	0	0	0	0
Totals	**0**	**1**	**0**	**0**	**0**	**1**	**2**

Yield(gpm)	1-49	50-99	100-499	500-999	>=1,000	NR	Totals
1-24	54	54	33	0	0	1	142
25-99	21	9	4	0	0	0	34
100-499	0	0	0	0	0	0	0
500-999	0	0	0	0	0	0	0
>1,000	0	0	0	0	0	0	0
NR	0	1	3	0	0	0	4
Totals	**75**	**64**	**40**	**0**	**0**	**1**	**180**

Figure 8-22. Wyoming SEO permitted and drilled domestic wells in the Wind River Mountains and Great Divide Basin Subregion.

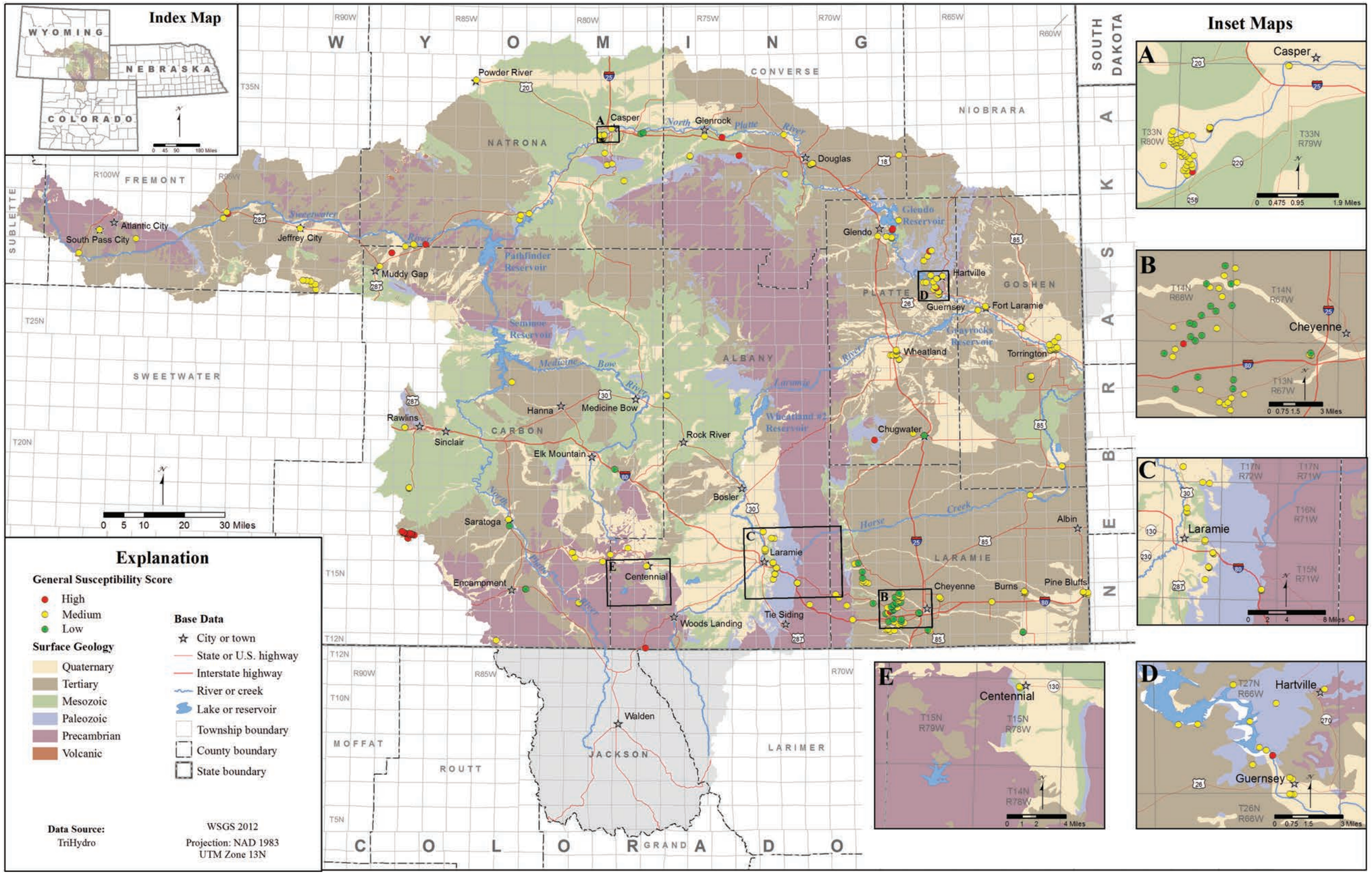


Figure 8-23. Surface Water Assessment and Protection, Platte River Basin, Wyoming.

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply (p. 341–345).

MUNICIPALITY Well Name	Public Water System ID	WSEO Permit No.	Yield (gpm)	Well Depth (ft)	Source Type	Producing Unit
Town of Albin						
ALBIN, TOWN OF	5600189-104	P42983W	139	0	Well	
ALBIN, TOWN OF	5600189-102	P4060W	500	0	Well	
Town of Bairoil						
BAIROIL, TOWN OF	5600003-109	P26764W	400	2002	Well	Battle Spring Fm
BAIROIL, TOWN OF	5600003-108	P26762W	400	2010	Well	Battle Spring Fm
BAIROIL, TOWN OF	5600003-105	P14776W	400	2084	Well	Battle Spring Fm
BAIROIL, TOWN OF	5600003-106	P14777W	1300	2010	Well	Battle Spring Fm
BAIROIL, TOWN OF	5600003-104	P14775W	300	2080	Well	Battle Spring Fm
BAIROIL, TOWN OF	5600003-107	P14793W	300	2043	Well	Battle Spring Fm
Town of Burns						
BURNS BD. OF PUBLIC UTILITIES	5600188-105	P97564W	325	240	Well	Ogallala Fm, Arikaree Fm, and White River Fm
BURNS BD. OF PUBLIC UTILITIES	5600188-101	P95259W	850	232	Well	Ogallala Fm, Arikaree Fm, and White River Fm
BURNS BD. OF PUBLIC UTILITIES	5600188-102	P1360W	12	200	Well	Ogallala Fm, Arikaree Fm, and White River Fm
BURNS BD. OF PUBLIC UTILITIES	5600188-104	P37502W	910	232	Well	Ogallala Fm, Arikaree Fm, and White River Fm
City of Cheyenne						
CHEYENNE BOARD PUB UTILITIES	5600011-108	P13G	400	395	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-110	P286C	325	210	Well	Ogallala
CHEYENNE BOARD PUB UTILITIES	5600011-109	P291C	350	361	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-111	P285C	475	291	Well	Ogallala
CHEYENNE BOARD PUB UTILITIES	5600011-135	<Null>	300	360	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-144	P289C	125	395	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-134	P282C	250	420	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-142	P284C	325	150	Well	Ogallala
CHEYENNE BOARD PUB UTILITIES	5600011-139	P281C	375	307	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-138	P280C	250	203	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-143	P287C	200	350	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-141	P275C	150	280	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-140	P290C	150	300	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-136	P270C	150	265	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-137	P271C	500	331	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-132	P268C	150	317	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-133	P266C	375	459	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-131	P269C	350	335	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-130	P265C	250	370	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-115	P477G	275	250	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-118	P480G	200	225	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-117	P479G	300	208	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-114	P476G	320	170	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-112	P474G	150	187	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-113	P475G	100	225	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-116	P478G	400	212	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-119	P43W	400	270	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-121	P45W	600	275	Well	Ogallala and White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-125	P341G	600	250	Well	White River,Lance, & Fox Hills Fms
CHEYENNE BOARD PUB UTILITIES	5600011-127	P257G	600	240	Well	White River Fm
CHEYENNE BOARD PUB UTILITIES	5600011-124	P256G	600	178	Well	White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-128	P43985W	600	297	Well	White River Fm
CHEYENNE BOARD PUB UTILITIES	5600011-126	P342G	600	245	Well	White River Fm
CHEYENNE BOARD PUB UTILITIES	5600011-129	P43986W	600	354	Well	White River Fm
CHEYENNE BOARD PUB UTILITIES	5600011-122	P278C	600	184	Well	White River Fms
CHEYENNE BOARD PUB UTILITIES	5600011-123	P279C		178	Well	White River Fms
Town of Chugwater						
CHUGWATER, TOWN OF	5600200-103	P1395W	300	128	Well	White River Fm
CHUGWATER, TOWN OF	5600200-102	P1394W	45	80	Well	White River Fm
CHUGWATER, TOWN OF	5600200-101	P1393W	45	0	Well	White River Fm
CHUGWATER, TOWN OF	5600200-104	P119526W	90	120	Well	White River Fm
CHUGWATER, TOWN OF	5600200-105	P154780W	300	380	Well	White River Fm
Town of Douglas						
DOUGLAS, TOWN OF	5600137-101			0	Spring	White River Fm
DOUGLAS, TOWN OF	5600137-102	P97415W	910	1165	Well	Casper Fm and Madison Limestone
Town of Fort Laramie						
FORT LARAMIE, TOWN OF	5600185-102	P9902W	2	82	Well	Alluvium
FORT LARAMIE, TOWN OF	5600185-103	P62637W	300	95	Well	Alluvium
Town of Glendo						
GLENDO, TOWN OF	5600231-101	P433C	225	410	Well	Chugwater Fm/Hartvile
Town of Glenrock						
GLENROCK, TOWN OF	5600199-101	P68630W	1100	250	Well	Casper Fm and Madison Limestone
GLENROCK, TOWN OF	5600199-102	P71254W	650	230	Well	Casper Fm and Madison Limestone
Town of Guernsey						
GUERNSEY, TOWN OF	5600023-103	P61817W	600	91	Well	Alluvium
GUERNSEY, TOWN OF	5600023-102	P95C	700	90	Well	Alluvium
GUERNSEY, TOWN OF	5600023-101	P1562W	12	188	Well	Alluvium

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply (cont.).

Town of Hartville						
HARTVILLE, TOWN OF	5600186-102	P71532W	600	65	Well	Alluvium
HARTVILLE, TOWN OF	5600186-101	P56437W	250	60	Well	Alluvium
HARTVILLE, TOWN OF	5600186-103	P114298W	270	200	Well	Metasedimentary Rocks
Town of La Grange						
LA GRANGE	5600788-102	P55679W	450	80	Well	White River Fm-Brule Member, locally includes upper conglomerate member
LA GRANGE	5600788-101	P55678W	450	80	Well	White River Fm-Brule Member, locally includes upper conglomerate member
City of Laramie						
LARAMIE, CITY OF	5600029-102	P105576W	1000	289	Well	Casper Fm
LARAMIE, CITY OF	5600029-106	P55506W	2500	350	Well	Casper Fm
LARAMIE, CITY OF	5600029-104	P154C	2500	162	Well	Casper Fm
LARAMIE, CITY OF	5600029-105	P155C	550	158	Well	Casper Fm
LARAMIE, CITY OF	5600029-103	P153C	515	156	Well	Casper Fm
LARAMIE, CITY OF	5600029-108	P55507W	590	240	Well	Casper Fm
LARAMIE, CITY OF	5600029-109	P55508W	1750	350	Well	Casper Fm
LARAMIE, CITY OF	5600029-110	P106547W	1400	305	Well	Casper Fm
LARAMIE, CITY OF	5600029-111	P107279W	1400	323	Well	Casper Fm
Town of Lingle						
LINGLE, TOWN OF	5600030-102	P8564W	500	70	Well	Alluvium and White River Fm
LINGLE, TOWN OF	5600030-101	P629W	600	82	Well	Alluvium and White River Fm
LINGLE, TOWN OF	5600030-103	P41620W	475	78	Well	Alluvium and White River Fm
Town of Medicine Bow						
MEDICINE BOW, TOWN OF	5600034-102	P69012W	139	660	Well	Casper Fm
MEDICINE BOW, TOWN OF	5600034-101	P399C	600	800	Well	Casper Fm
Town of Mills						
MILLS, TOWN OF	5600036-102	P13699W	300	35	Well	Alluvium
MILLS, TOWN OF	5600036-103	P1252W	300	40	Well	Alluvium
MILLS, TOWN OF	5600036-104	P1253W	500	40	Well	Alluvium
MILLS, TOWN OF	5600036-106	P153071W	325	35	Well	Alluvium
MILLS, TOWN OF	5600036-105	P1254W	160	38	Well	Alluvium
MILLS, TOWN OF	5600036-107	P4588W	600	40	Well	Alluvium
MILLS, TOWN OF	5600036-109	P50607W	450	40	Well	Alluvium
Town of Pine Bluffs						
PINE BLUFFS, TOWN OF	5600040-101	P295C	375	125	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-102	P124G	325	125	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-103	P130992W	500	0	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-104	P13170W	850	130	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-105	P3994W	850	0	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-106	P298C	1110	120	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-107	P152302	1300	120	Well	White River Fm, Brule member
PINE BLUFFS, TOWN OF	5600040-108	P152191W	1300	100	Well	White River Fm, Brule member
City of Rawlins						
RAWLINS WATER SUPPLY, CITY OF	5600045-101a	P70332W	350	1730	Well	Nugget Sandstone
RAWLINS WATER SUPPLY, CITY OF	5600045-101b	P70333W	500	1743	Well	Nugget Sandstone
RAWLINS WATER SUPPLY, CITY OF	5600045-101c	P70334W	500	1625	Well	Nugget Sandstone
RAWLINS WATER SUPPLY, CITY OF	5600045-107	P6241E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-108	P6242E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-109	P6243E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-110	P6246E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-111	P6245E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-112	P6247E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-113	P6248E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-114	P6254E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-115	P6249E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-116			0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-117	P6251E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-118	P6253E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-119	P6256E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-120	P6255E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-121	P6258E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-122	P6257E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-123	P6261E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-124	P6260E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-125	P6259E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-126	P6262E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-127	P6240E	700	0	Spring	Miocene Rock
RAWLINS WATER SUPPLY, CITY OF	5600045-128			0	Spring	Miocene Rock
Town of Rolling Hills						
ROLLING HILLS, TOWN OF	5600782-102	P64210W	600	0	Well	
ROLLING HILLS, TOWN OF	5600782-103	P64211W	600	0	Well	
ROLLING HILLS, TOWN OF	5600782-104	P70662W	500	0	Well	
ROLLING HILLS, TOWN OF	5600782-105	P81833W	40	0	Well	
City of Torrington						
TORRINGTON MUN. WATER SYSTEM	5600164-101	P439C	400	60	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-102	P440C	800	60	Well	Alluvium

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply (cont.).

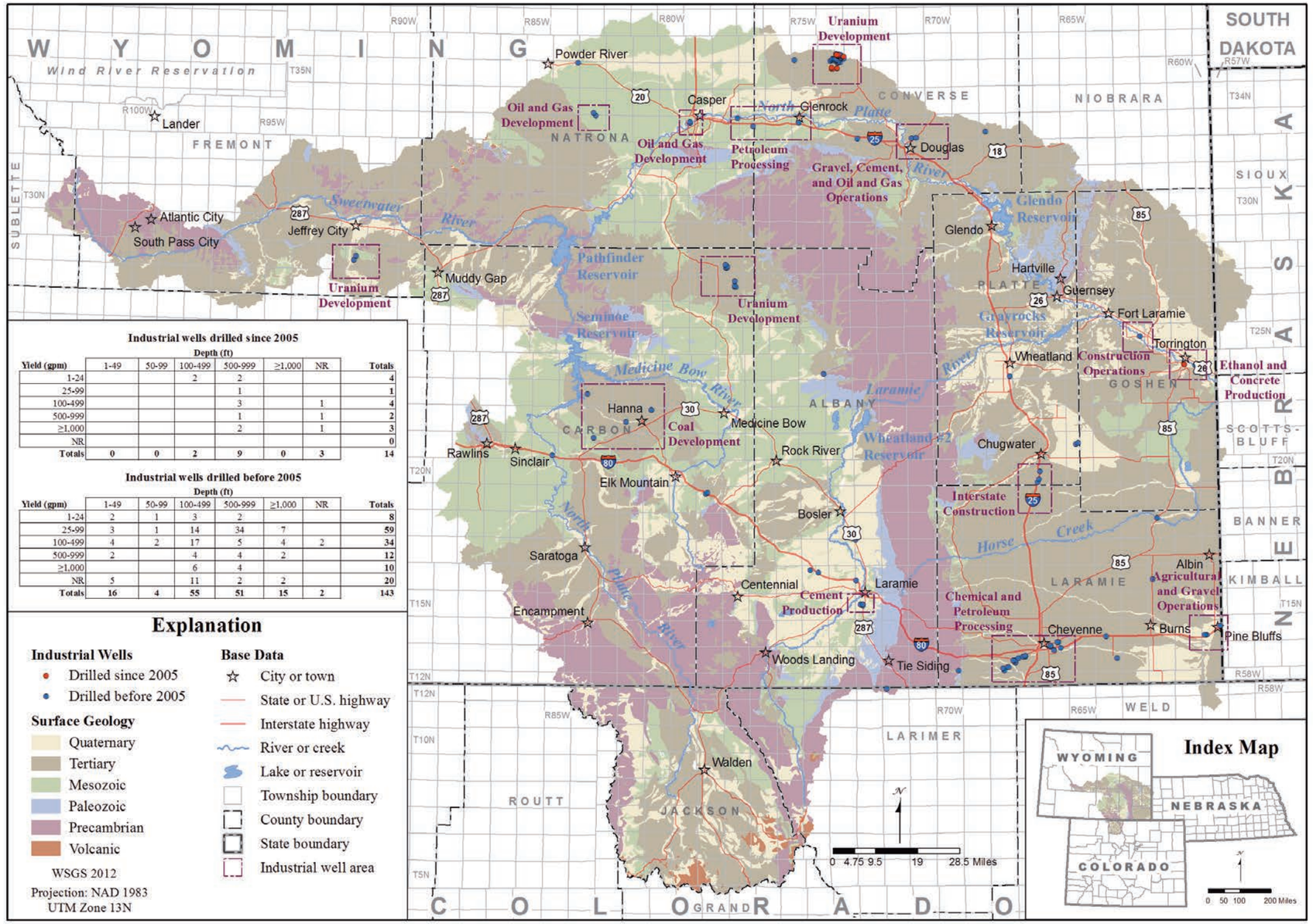
TORRINGTON MUN. WATER SYSTEM	5600164-103	P156G	750	90	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-104	P868W	750	83	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-105	P2629W	1000	100	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-106	P45138W	800	125	Well	Terrace
TORRINGTON MUN. WATER SYSTEM	5600164-107	P45139W	800	65	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-108	P14789W	1300	175	Well	Terrace
TORRINGTON MUN. WATER SYSTEM	5600164-109	P69070W	950	128	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-110	P65949W	600	70	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-111	P144751W	400	182	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-112	P144749W	400	177	Well	Alluvium
TORRINGTON MUN. WATER SYSTEM	5600164-113	P144750	400	179	Well	Alluvium
Town of Wheatland						
WHEATLAND, TOWN OF	5600187-101	P90W	750	450	Well	Arikaree and White River Fms
WHEATLAND, TOWN OF	5600187-102	P107W	2500	506	Well	Dune Sand and LoessArikaree and White River Fms
WHEATLAND, TOWN OF	5600187-103	P109C	600	560	Well	Dune Sand and LArikaree and White River Fmsoess
WHEATLAND, TOWN OF	5600187-104	P490C	550	503	Well	Dune Sand and Arikaree and White River FmsLoess
WHEATLAND, TOWN OF	5600187-105	P491G	550	490	Well	Dune Sand and Arikaree and White River FmsLoess
WHEATLAND, TOWN OF	5600187-106	P48832W	475	585	Well	Dune Sand andArikaree and White River Fms Loess
WHEATLAND, TOWN OF	5600187-107	P55321W	300	619	Well	Dune Sand and Arikaree and White River FmsLoess
Town of Yoder						
YODER WATER SYSTEM, TOWN OF	5600169-101	P94572W	25	185	Well	White River Fm - Chadron member
YODER WATER SYSTEM, TOWN OF	5600169-102	P81444W	40	195	Well	White River Fm - Chadron member
YODER WATER SYSTEM, TOWN OF	5600169-103	P94573W	12	193	Well	White River Fm - Chadron member
YODER WATER SYSTEM, TOWN OF	5600169-104	P138952W	45	160	Well	White River Fm - Chadron member
Wells without known Municipality						
<Null>	5601331-101	P63195W	600	110	Well	Fox Hills Sandstone
<Null>	5601459-101	P65952W	600	200	Well	Fox Hills Sandstone
<Null>	5601460-101			215	Well	Fox Hills Sandstone
<Null>	5680047-101	P48839W	475	135	Well	
<Null>	5680170-101	P48850W	475	95	Well	
<Null>	5680233-101			126	Well	Miocene Rocks
A BAR A RANCH	5600334-102			50	Well	Alluvium
A BAR A RANCH	5600334-103			58	Well	Alluvium
AAA MOBILE HOME PARK	5601265-101	P81139W	270	0	Well	White River Fm
AAA MOBILE HOME PARK	5601265-102	P81140W	270	500	Well	White River Fm
ALBANY BAR-LODGE INC	5600301-101	P48557W	600	65	Well	
ALCOVA SCHOOL-NATRONA CTY S.D.	5601053-101	P100915W		49	Well	Cloverly, Morrison, Sundance Fms
ALPINE INN (DOUGLAS PROP. INC)	5600320-101	P30272W	1110	120	Well	White River Fm
ANTELOPE RIDGE H.O.A.	5601457-101	P99820W	300	0	Well	Casper Fm
ANTELOPE RIDGE H.O.A.	5601457-102	P99821W	300	1280	Well	Casper Fm
ARLINGTON OUTPOST	5600068-101	P57763W	250	280	Well	
ARMY NAT GRD TRNG SITE-SPRING	5680203-101			387	Well	Hartville Fm
ARMY RESERVE NAT GRD TRNG SITE-WELLS	5600797-101	P85899W	475	196	Well	Alluvium
ARMY RESERVE NAT GRD TRNG SITE-WELLS	5600797-102	P95391W	12	305	Well	Alluvium
ARMY RESERVE NAT GRD TRNG SITE-WELLS	5600797-103	P80109W	270	77	Well	Alluvium
ARNG-DEERCORN SPRINGS WL#4-CAMP GUERNSEY	5601433-101	P79239W	270	387	Well	Hartville Fm
ARNG-LAW RANGE WELL #5-CAMP GUERNSEY	5601432-101	P79240W	270	401	Well	Hartville Fm
ARNG-RYAN SPRINGS WELL #6-CAMP GUERNSEY	5601434-101	P79241W	270	400	Well	Hartville Fm
ATLANTIC CITY MERCANTILE, INC.	5600432-101	P39366W	850	80	Well	
BIG EAGLE MINE TOWNSITE	5600271-101			100	Well	Arikaree Fm
BLM LODGEPOLE CAMPGROUND	5680146-101	P27093W	250	175	Well	Sandstones of Cloverly, Morrison, and Sundance Fms
BLM LODGEPOLE CAMPGROUND	5680146-102	P27094W	250	125	Well	Sandstones of Cloverly, Morrison, and Sundance Fms
BROKEN WHEEL TRUCK STOP	5601001-101	P2798W	200	100	Well	White River Fm
BROKEN WRENCH LLC	5600074-101	P4943W	550	51	Well	Cody Shale
CAMP SACAJAWEA	5600856-101	P54927W	175	160	Well	Metamorphosed Mafic and Ultra Mafic Rocks
CAMP SACAJAWEA	5600856-102			0	Spring	Metamorphosed Mafic and Ultra Mafic Rocks
CAMP SACAJAWEA	5600856-103	P80074W	270	62	Well	Metamorphosed Mafic and Ultra Mafic Rocks
CAMP WYOBA AND LIONS CLUB	5600685-101	P48489W	600	10	Well	
CARPENTER WATER & SEWER DIST	5601464-101	P102858W		500	Well	White River Fm, Chadron member
CARPENTER WATER & SEWER DIST	5601464-102	P112792W	600	480	Well	White River Fm, Chadron member
CATHEDRAL HOME	5600880-101	P13605W	850	1010	Well	Casper Fm
CENTENNIAL WATER AND SEWER	5601232-101	P81280W	45	740	Well	Casper Fm
CENTENNIAL WATER AND SEWER	5601232-102	P83020W	50	860	Well	Casper Fm
CENTRAL WY REG WATER SYS JPB	5600009-101c10	P600G	600	28	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c11	P49W	750	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c12	P50W	750	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c14	P601G	600	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c15	P602G	800	34	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c19	P103719W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c20	P104440W	1000	37	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c21	P103721W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c22	P103722W	1000	39	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c5	P595G	700	34	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c6	P596G	700	36	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c7	P597G	700	34	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c8	P598G	600	32	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101c9	P599G	700	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101cs1	P104429W	1000	38	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101cs2	P103720W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101cs3	P104430W	1000	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m10	P103730W	1000	38	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m11	P103731W	1000	0	Well	Alluvium

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply (cont.).

CENTRAL WY REG WATER SYS JPB	5600009-101m12	P103732W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m13	P103733W	1000	36	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m2	P1798W	700	39	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m3	P1799W	700	43	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m4	P104431W	1000	30	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m5	P103737W	1000	42	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m6	P103736W	1000	42	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m7	P103727W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m8	P103728W	1000	0	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-101m9	P103729W	1000	34	Well	Alluvium
CENTRAL WY REG WATER SYS JPB	5600009-104	P617C	500	31	Well	Alluvium
COASTAL CHEM, INC.	5600910-101	P1703W	750	195	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-102	P1755W	750	265	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-103	P82585W	40	350	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-104	P41093W	139	250	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-105	P57114W	250	260	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-106	P74548W	270	290	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-107	P85277W	100	273	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-108	P85278W	100	283	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-109	P85279W	100	190	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-110	P121580W	300	335	Well	Ogallala Fm
COASTAL CHEM, INC.	5600910-111	P121581W	300	330	Well	Ogallala Fm
COTTONWOOD ACRES	5601233-101	P78043W	270	85	Well	Alluvium/Colluvium
COTTONWOOD ACRES	5601233-102	P78044W	270	85	Well	Alluvium/Colluvium
COTTONWOOD ACRES	5601233-103	P67295W	600	60	Well	Alluvium/Colluvium
COTTONWOOD ACRES	5601233-104	P67294W	600	60	Well	Alluvium/Colluvium
COUNTRY MEADOW ESTATES	5600162-101	P29196W	200	130	Well	Casper Fm
COUNTRY MEADOW ESTATES	5600162-102	P1050W	1000	125	Well	Casper Fm
COUNTRY MEADOW ESTATES	5600162-103	P49225W	550	190	Well	Casper Fm
COUNTRY SIDE COURT	5600756-101	P46998W	600	50	Well	Alluvium/Colluvium
CURT GOWDY ST PK HEADQUARTERS	5600866-101	P26405W	1000	250	Well	Sherman Granite
CURT GOWDY ST PK N GRANITE SPR	5600867-101	P25987W	350	103	Well	Sherman Granite
CURT GOWDY ST PK S GRANITE SPR	5600868-101	P101126W		135	Well	Sherman Granite
CURT GOWDY ST PK S GRANITE SPR	5600868-102	P20222W	700	0	Well	Sherman Granite
CURT GOWDY ST PK-CRYSTAL DAM OVERLOOK	5601222-101	P72798W	270	120	Well	White River Fm and Sherman Granite
DAVE JOHNSTON POWER PLANT	5600291-102	P1540W	550	15	Well	Alluvium
DEER HAVEN MOBILE HOME PARK	5600225-101	P40224W	139	130	Well	North Park Fm
DEER HAVEN MOBILE HOME PARK	5600225-102	P40225W	139	90	Well	North Park Fm
DIAMOND GUEST RANCH	5600580-101			0	Spring	Wells and Amsden Fms
DILLMAN ESTATES	5601248-101	P69465W	950	80	Well	Alluvium/Colluvium
ECUMENICAL RETREAT CENTER	5601049-101	P41910W	500	295	Well	
ECUMENICAL RETREAT CENTER	5601049-102	P63302	600	0	Well	
FAIRWAY ESTATES	5600918-101	P42804W	500	160	Well	White River Fm
FAIRWAY ESTATES	5600918-102	P42805W	500	160	Well	White River Fm
FAIRWAY ESTATES	5600918-103	P42806W	500	160	Well	White River Fm
FAIRWAY ESTATES	5600918-104	P77530W	270	170	Well	White River Fm
FAIRWAY ESTATES	5600918-105	P105445W	1000	0	Well	White River Fm
FIRST CHURCH OF THE NAZARENE	5601238-101	P41986W	500	140	Well	
FLYING J	5600102-101	P1488W	1300	200	Well	Miocene Rocks
FLYING J	5600102-102	P1489W	1300	100	Well	Miocene Rocks
FLYING J	5600102-103			200	Well	Miocene Rocks
FLYING J	5600102-104	P26400W	1000	200	Well	Miocene Rocks
FLYING J	5600102-105	P26401W	1000	0	Well	
FLYING X RANCH MOBILE HM PARK	5601104-101	P42979W	500	245	Well	
FLYING X RANCH MOBILE HM PARK	5601104-103	P91965W	750	250	Well	
FLYING X RANCH MOBILE HM PARK	5601104-104	P23766W	700	48	Well	
FORT FETTERMAN STATE HIST SITE	5680174-101	P91508W	750	380	Well	Fort Union
FORT LARAMIE NAT`L HIST SITE	5680115-101	P6445W	600	60	Well	Alluvium
FORT LARAMIE NAT`L HIST SITE	5680115-102	P6446W	600	60	Well	Alluvium
FORT LARAMIE, TOWN OF	5600185-101	P95G	825	80	Well	Alluvium
GILCHRIST ELEMENTARY	5601025-101	P62542W	700	360	Well	White River Fm, Brule member
GLENDO ST PARK COTTONWOOD	5600665-101	P35526W	150	120	Well	White River Fm
GLENDO ST PARK HEADQUARTERS	5600661-101	P27171W	325	300	Well	Cloverly and Morrison Fms
GLENDO ST PARK HEADQUARTERS	5600661-102	P41400W	139	178	Well	Cloverly and Morrison Fms
GLENDO ST PARK HEADQUARTERS	5600661-103	P90120W	750	304	Well	Cloverly and Morrison Fms
GLENDO ST PARK HEADQUARTERS	5600661-104	P146196W	400	560	Well	Cloverly and Morrison Fms
GLENDO ST PARK RED HILLS	5600663-101	P35527W	150	130	Well	White River Fm
GLENDO ST PARK RENO COVE	5600662-101	P7946W	270	145	Well	White River Fm
GLENDO ST PARK WHISKEY GULCH	5600664-101	P27170W	325	200	Well	White River Fm
GLENROCK SOUTH RECREATION COMP	5601069-101	P40235W	139	24	Well	Alluvium
GRANITE CANYON QUARRY	5601146-101	P110063W	600	95	Well	Metasedimentary & Metavolcanic Rocks
GRANITE CANYON QUARRY	5601146-102	P110042W	600	0	Well	Metasedimentary & Metavolcanics
GRASSLANDS RESTAURANT AND SALOON	5600323-101	P1524W	1300	85	Well	White River Fm
GUERNSEY ST PARK BLACK CANYON	5680178-101	P72797W	270	60	Well	Hartville Fm
GUERNSEY ST PARK EAST SIDE	5600689-101	P28552W	150	204	Well	Hartville Fm
GUERNSEY ST PARK FISH CANYON	5600690-101	P7947W	270	352	Well	Hartville Fm
GUERNSEY ST PARK HEADQUARTERS	5680177-101	P28561W	150	40	Well	Hartville Fm
GUERNSEY ST PARK LONG CANYON	5600691-101	P27168W	325	139	Well	Hartville Fm
GUERNSEY ST PARK SANDY BEACH 1	5600693-101	P7948W	270	140	Well	Lower Miocene Upper Oligocene Rocks
GUERNSEY ST PARK SANDY BEACH 2	5600694-101	P27169W	325	140	Well	Lower Miocene and Upper Oligocene Rocks
GUERNSEY ST PARK SEWER DUMP	5600692-101	P20225W	700	260	Well	Hartville Fm(Database)
HALL'S GLENDO MARINA	5600309-101	P25274W	700	200	Well	
HOGADON SKI AREA	5600736-101	P69857W	950	120	Well	
HOLDINGS LITTLE AMERICA	5600485-101	P1185W	600	143	Well	White River Fm, Brule member
HOLDINGS LITTLE AMERICA	5600485-102	P29627W	375	200	Well	White River Fm, Brule member

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply (cont.).

HOLDINGS LITTLE AMERICA	5600485-104			200	Well	White River Fm, Brule member
HOLDINGS LITTLE AMERICA	5600485-105	P96254W	825	145	Well	White River Fm, Brule member
HOLDINGS LITTLE AMERICA	5600485-106	P96255W	825	155	Well	White River Fm, Brule member
JEFFREY CITY HOA	5600106-101	P52W	175	152	Well	Arikaree Fm
JEFFREY CITY HOA	5600106-102	P31835W	500	241	Well	Arikaree Fm
KOA JACKALOPE CAMPGROUND	5600247-101	P9814W	910	200	Well	
LAKE WATER CO., LTD.	5600509-101	P1255W	500	278	Well	
LAKE WATER CO., LTD.	5600509-102	P91170W	750	275	Well	
LARSON'S PARK	5601376-101	P86235W	165	0	Well	
LONGBRANCH STEAKHOUSE & SALOON	5600711-101			0	Well	Lance Fm
LORD OF LORDS LUTHERAN CHURCH	5600972-101	P66872W	600	220	Well	
LOST BAR	5600507-101	P85289W	100	380	Well	Lower Miocene Upper Oligocene Rock
MED BOW NF-S BRUSH CR CG-UPPER	5680055-101	P48845W	475	120	Well	Granitic Rock of the 2600Ma Age Group
MED.BOW NF-S BRUSH CR CG-LOWER	5680054-101	P48846W	475	120	Well	Granitic Rock of the 2600Ma Age Group
MEDICINE BOW GUEST RANCH	5600986-101	P43972W	225	33	Well	
MEDICINE BOW MINE	5601387-101	P51115W	750	600	Well	Ferris Fm
MEDICINE BOW NF HIDDEN VALL PG	5680062-101	P1165W	600	50	Well	Sherman Granite
MEDICINE BOW NF- LAKEVIEW CG	5680176-101	P66919W	600	946	Well	Granitic Rocks of the 1700Ma Age Group
MEDICINE BOW NF MIRROR LAKE CG	5680050-101	P48848W	475	60	Well	Libby Creek Group
MEDICINE BOW NF NASH FORK CG	5680060-101	P79758W	270	50	Spring	Granitic Rock of the 2600Ma Age Group
MEDICINE BOW NF RYAN PARK CG	5680051-101	P48841W	475	60	Well	Glacial Deposits
MEDICINE BOW NF SILVER LAKE CG	5680052-101	P49658W	550	95	Well	Libby Creek Group
MEDICINE BOW NF VEDAUWOO CG	5680068-101	P1546	550	45	Well	Sherman Granite
MHVC 66 RANCH	5601446-101	P109762W	2500	40	Well	Alluvium
MHVC 66 RANCH	5601446-102	P109763W	2500	40	Well	Alluvium
MHVC CHERRY CREEK CG	5601444-101	P105021W	1000	120	Well	Alluvium
MHVC JACKSON CG	5601445-101	P107992W	2500	120	Well	Miocene Rocks
MHVC SIXTH CROSSING RANCH RV PARK	5601487-101	P134775W	850	60	Well	Alluvium
MHVC SIXTH CROSSING RANCH RV PARK	5601487-102	P134778W	850	78	Well	Miocene Rocks
MHVC VISITORS CENTER	5601431-101	P109516W	2500	120	Well	Alluvium
MHVC VISITORS CENTER	5601431-102	P8472P	100	38	Well	Alluvium
MHVC VISITORS CENTER	5601431-103	P105022W	1000	120	Well	Alluvium
MILLER LOWER MOBILE HOME PARK	5600051-101	P15956W	750	180	Well	White River Fm
MILLS SPRING CAMP-7TH DAY ADV.	5600631-102	P43964W	225	160	Well	
NATRONA COUNTY PARK BEARTRAP	5600678-101	P2543W	700	130	Well	Granitic Schist
NATRONA COUNTY PARKS-ALCOVA PK	5600677-101	P2541W	700	375	Well	Chugwater Fm
OX YOKE RANCH	5601030-101			65	Well	Sherman Granite
POTLATCH TRAILER COURT	5600171-101	P14837W	1300	50	Well	Alluvium
POWDER RIVER AREA WELL	5600584-101	P107884W	2500	40	Well	Dune Sand and Loess
RIVERSIDE TRAILER COURT	5600072-101	P18658P	700	53	Well	Alluvium
RIVERSIDE TRAILER COURT	5600072-102	P18659P	700	53	Well	Alluvium
ROCK CREEK HOLLOW-LDS CHURCH	5601438-101	P105644W	1000	64	Well	Metasedimentary Rocks
SHANNON HEIGHTS	5600265-101	P5642W	450	320	Well	White River Fm
SHANNON HEIGHTS	5600265-102	P50236W	750	136	Well	White River Fm
SHANNON HEIGHTS	5600265-103	P50237W	750	184	Well	White River Fm
SHRINE CLUB	5601102-101	P1694W	750	280	Well	
SIERRA MADRE JPB	5601332-101	P83219W	100	215	Well	North Park Fm
SIERRA MADRE JPB	5601332-102	P85902W	165	622	Well	North Park Fm
SOUTH PASS CITY HIST SITE	5601137-101	P6132P	800	35	Well	Alluvium
THREE FORKS-MUDDY GAP SERVICE	5601326-101	P75088W	270	319	Well	Miocene Rocks
WESTWOOD TRLR CT ATT:W WERKELE	5600170-102	P41826W	500	110	Well	Alluvium
WESTWOOD TRLR CT ATT:W WERKELE	5600170-103	P112112W	600	67	Well	Alluvium
WINCHESTER HILLS	5600779-101	P46996W	600	860	Well	White River Fm
WINCHESTER HILLS	5600779-102	P46997W	600	485	Well	White River Fm
WINCHESTER HILLS	5600779-103	P68555W	600	700	Well	White River Fm
WINDY WATERS MOBILE HOME & RV PARK	5600870-101	P48104W	600	100	Well	Alluvium
WY DEPT OF TRANS-INFORMATION CTR	5600622-101	P28075W	150	220	Well	
WY TRANS DEPT E. GUERNSEY RA	5600642-101	P28548W	150	382	Well	
WY TRANS DEPT E. GUERNSEY RA	5600642-102	P12808W	500	280	Well	
WY TRANS DEPT I-25 PORT OF ENT	5600944-101	P55178W	175	260	Well	
WY TRANS DEPT I-80 PORT OF ENT	5600845-101	P55306W	175	300	Well	
WY TRANS DEPT INDEPENDENCE RK	5601162-101	P80471W	270	200	Well	
WY TRANS DEPT MERIDAN RA	5600921-101	P66648W	600	161	Well	White River Fm, Brule member
WY TRANS DEPT NB I-25 RA	5600643-101	P16717W	750	230	Well	
WY TRANS DEPT PORT OF ENTRY 85	5601092-101	P61855W	700	497	Well	
WY TRANS DEPT S.B. I-25 RA	5600644-101	P16716W	750	223	Well	
WY TRANS DEPT SO. PASS REST AR	5600965-101	P53474W	175	200	Well	Upper Miocene Rocks, Metasedimentary Rocks
WY TRANS DEPT SUMMIT REST AREA	5600310-101	P2180W	700	222	Well	Sherman Granite
WY TRANS DEPT SUMMIT REST AREA	5600310-102	P2181W	700	202	Well	Sherman Granite
WY TRANS DEPT SWEETWATER RA	5601043-101	P74404W	270	100	Well	Miocene Rock
WY TRANS DEPT WAGONHOUND RA	5600825-101	P42908W	500	195	Well	Hanna Fm
WYOMING CAMPGROUND	5601291-thA	P104361W	1000	280	Well	Upper Miocene Rocks
WYOMING CAMPGROUND	5601291-thB	P33947W	500	205	Well	Upper Miocene Rocks
WYOMING TECHNICAL INSTITUTE	5600208-101	P9911W	300	1300	Well	Casper Fm
WYOMING TECHNICAL INSTITUTE	5600208-102	P75082W	270	1500	Well	Casper Fm
Y-O INVESTMENTS, INC.	5600777-101	P44726W	800	500	Well	Arikaree Fm
Y-O INVESTMENTS, INC.	5600777-102	P44727W	800	500	Well	Arikaree Fm



Industrial wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24			2	2			4
25-99				1			1
100-499				3		1	4
500-999				1		1	2
≥1,000				2		1	3
NR							0
Totals	**0**	**0**	**2**	**9**	**0**	**3**	**14**

Industrial wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	2	1	3	2			8
25-99	3	1	14	34	7		59
100-499	4	2	17	5	4	2	34
500-999	2		4	4	2		12
≥1,000			6	4			10
NR	5		11	2	2		20
Totals	**16**	**4**	**55**	**51**	**15**	**2**	**143**

Figure 8-24. Wyoming SEO, Colorado DWR, and Nebraska DNR permitted and drilled industrial wells.

Figure 5-4 shows the locations of conventional oil and gas fields in the Platte River Basin, where groundwater is produced as a byproduct. Conventional oil and gas operations in the Platte River Basin co-produced an average of 2,467 ac-ft of water per year from 2005 through 2011 (**Table 8-1b**: WOGCC, 2011). There are several options for managing water coproduced with conventional oil and gas and CBM operations. The viability of these, however, is dependent on the quality and the volume of the water produced:

- Underground injection for storage, permanent disposal, or enhanced recovery (water flooding, pressure maintenance)
- Infiltration from unlined pits and subsurface structures (tinhorns and other Class V injection facilities – generally no longer allowed)
- Evaporation from pits, landspreading, and landfarming
- Surface discharge for surface flows and associated uses:
    - domestic use (rare)
    - wildlife and livestock watering
    - wetlands, fish, and other aquatic wildlife habitat maintenance
    - irrigation
- General industrial uses:
    - drilling
    - road application and dust control
    - fire control
    - washing
    - power generation

Figures 5-4 and 5-5 show the location of Class II and Class I injection wells that can inject produced water from oil and gas operations for a variety of purposes. The WOGCC, BLM, and EPA permit Class II wells to operators for disposal of their own produced water. The WDEQ permits Class I wells for disposal of non-hazardous wastewaters from a variety of sources. The WOGCC and BLM also permit evaporation pits for disposal of produced water, generally in the field of origin (**Figure 5-4**). **Figure 5-7** shows the location of commercial disposal pits where produced water and other non-hazardous water (by RCRA criteria) from a variety of sources is permitted to evaporate.

Produced water of suitable quality can be put to beneficial use (e.g., stock watering, agriculture, drilling and industrial dust suppression). Otherwise, produced water is primarily discharged to the surface under the regulation of WDEQ NPDES/WYPDES permits or re-injected for enhanced recovery of oil and gas from depleted reservoirs or strictly as a means of disposal. An average of 1,174 ac-ft/yr of produced water was re-injected from 2005 through 2011 (**Table 8-1b**: WOGCC, 2011). Estimates of the volume of produced water discharged in the Platte River Basin under the WYPDES program are not readily available.

Produced water volumes that are discharged to the surface or put to other uses are generally considered to be partially-consumptive and, in a few cases, wholly consumptive. Almost every produced water management strategy involves some consumptive losses from evapotranspiration. On the other hand, injecting produced water into hydrogeologic units at depths where there is minimal chance of future withdrawal effectively removes it from the water budget of the basin and is wholly consumptive. In fact, most produced water probably would not have been withdrawn for any other use, and is discharged to the surface where it adds to streamflows and increases the growth of vegetation. The water balance developed within this study calculated net produced water volumes by deducting injected volumes from total produced water estimates. Outflows from the Platte River Basin were then adjusted by subtracting net produced water from outgoing streamflows. In turn, the amount of injected produced water was included in total (surface and groundwater) industrial use and subtracted from "precipitation remaining in the Platte River Basin" **(Table 8-2a)**. Alternately, it may be more appropriate not to consider produced water on either side of the water balance.

Produced water withdrawals in the Platte River Basin are primarily associated with conventional oil and gas operations, with lesser amounts for CBNG and historic uranium and coal mining. In conventional oil and gas production, groundwater is produced as a byproduct that is primarily disposed of using various methods; a smaller amount is used beneficially during production, refining or

associated operational activities (e.g., drilling, dust suppression). In contrast, groundwater extraction is integral to CBNG operations because the hydraulic pressure in the host coal beds must be lowered to liberate adsorbed methane. Groundwater production for CBNG production is considered to be a beneficial use in Wyoming, and groundwater appropriation permits must be obtained from the SEO in addition to drilling and production permits from the WOGCC and/or BLM (depending on mineral ownership). Water rights for CBNG withdrawals are, therefore, included in the SEO database (CBM) compiled for this project, while produced water withdrawals from conventional oil and gas operations are not, unless the water is put to a beneficial use.

CBNG development in the Platte River Basin has been insignificant compared with that in other basins like the Powder, Tongue and Green River drainages. A review of WOGCC records indicates there have been no producing CBNG wells in the Platte River Basin since 2005. However, coal seams with potential for CBNG production are present in the Platte River Basin, and it is likely that coalbed groundwater and methane will be produced in the future. Groundwater production on the order of 5–15 gpm per well is generally required for efficient CBNG production. As of January 2013, approximately 2,640 acre-feet of groundwater have been withdrawn during CBNG operations in the Platte River Basin (WOGCC, 2012).

8.4.4.6.2 Groundwater use for coal and uranium mining

Coal and uranium mining operations require ground and surface water withdrawals associated with several mining processes. The most important include mine de-watering, mineral extraction, milling and processing operations, mine reclamation, dust suppression and personnel uses. In many cases, mining operations will reuse produced water of sufficient quality for other operations such as dust suppression. Otherwise, surplus water is commonly discharged, under regulatory permit, to pits and/or surface drainage where a part is consumptively lost to evapotranspiration and the remainder returns to shallow aquifers through infiltration.

Currently there is no active coal or conventional uranium mining in the Platte River Basin. However, in-situ recovery (ISR) methods are currently being employed to mine uranium at the Highland Smith Ranch ISL Uranium Project approximately 20 miles northeast of Glenrock. Plans for additional ISR mines in several locations in the Platte River Basin are under review by federal and state regulatory agencies. ISR mining entails circulating a leaching solution of water and sodium bicarbonate through a mineralized zone and then pumping the mineralized solution to the surface where the uranium is extracted. In the ISR process, most groundwater ultimately remains in the aquifer, with approximately 1 percent withdrawn to maintain negative formation pressure. Another 0.01 percent of the circulated water is removed as brine waste-product that is injected into deeper formations through permitted wells.

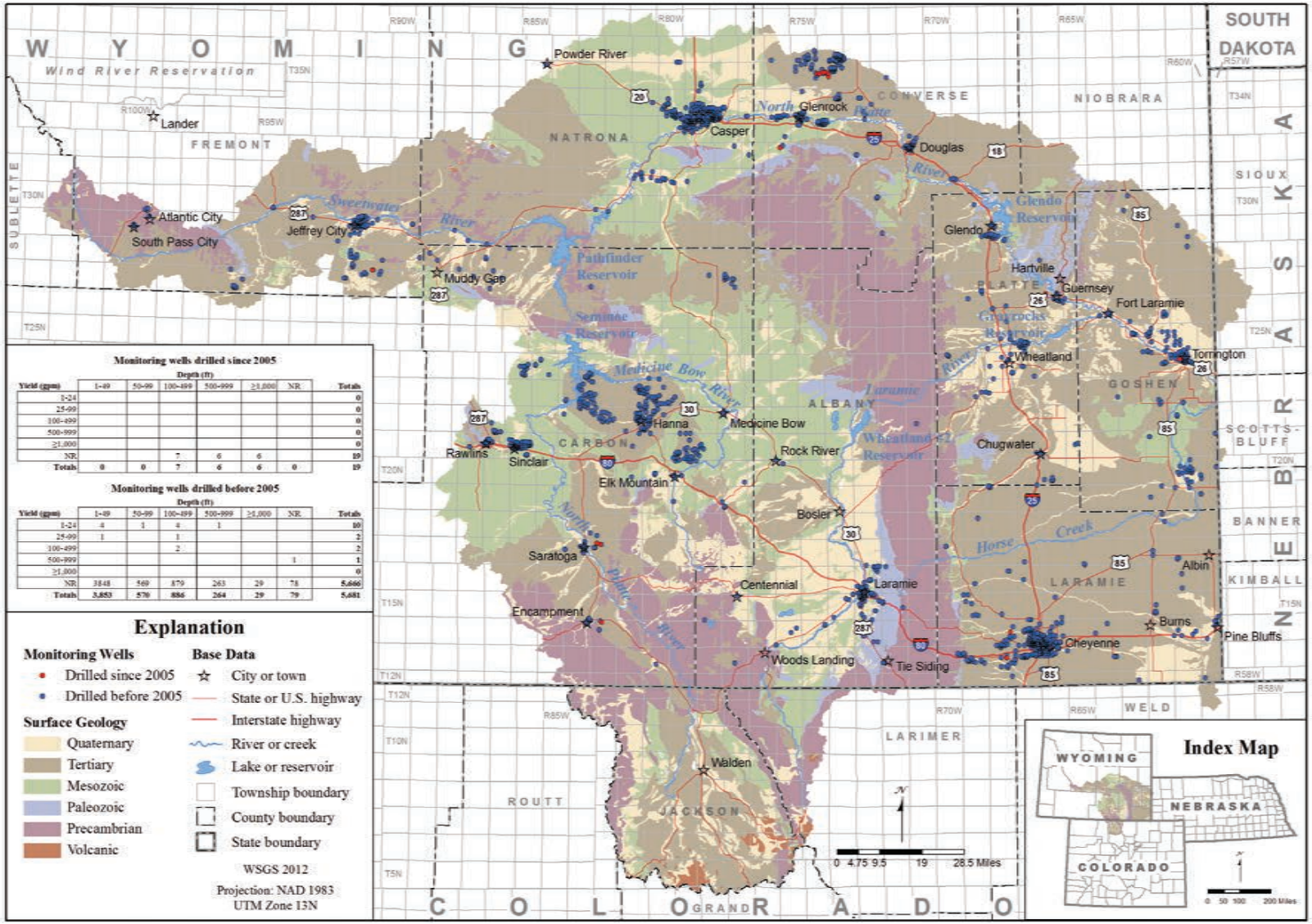
The Carbon Basin coal liquefaction project and future development of the abundant coal resources of the Platte River Basin, primarily in the Hanna Basin, will likely require groundwater withdrawals. **Figures 5-7** and **5-8** show the distribution of coal and uranium mines in the Platte River Basin.

8.4.4.6.3 Groundwater use for non-energy minerals development

Groundwater withdrawals for non-energy minerals development in the Platte River Basin are primarily for aggregate, gravel, and cement production. **Figure 8-24** shows the locations of groundwater permits for these uses in the Platte River Basin.

8.4.4.7 Monitoring wells

Table 8-6 lists 9,188 SEO groundwater permits for monitoring wells in the Platte River Basin. Monitoring wells are typically used to monitor the levels and the quality of groundwater associated with a contaminated site or a potentially contaminated site (e.g., underground fuel storage tank) or to monitor for groundwater impacts from various activities (e.g., mining, waste management). When used for monitoring alone, these wells have no permitted yield; however, there may be a



Monitoring wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR			7	6	6		19
Totals	0	0	7	6	6	0	19

Monitoring wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	4	1	4	1			10
25-99	1		1				2
100-499			2				2
500-999						1	1
≥1,000							0
NR	3848	569	879	263	29	78	5,666
Totals	3,853	570	886	264	29	79	5,681

Figure 8-25. Wyoming SEO, Colorado DWR, and Nebraska DNR permitted and drilled monitoring wells.

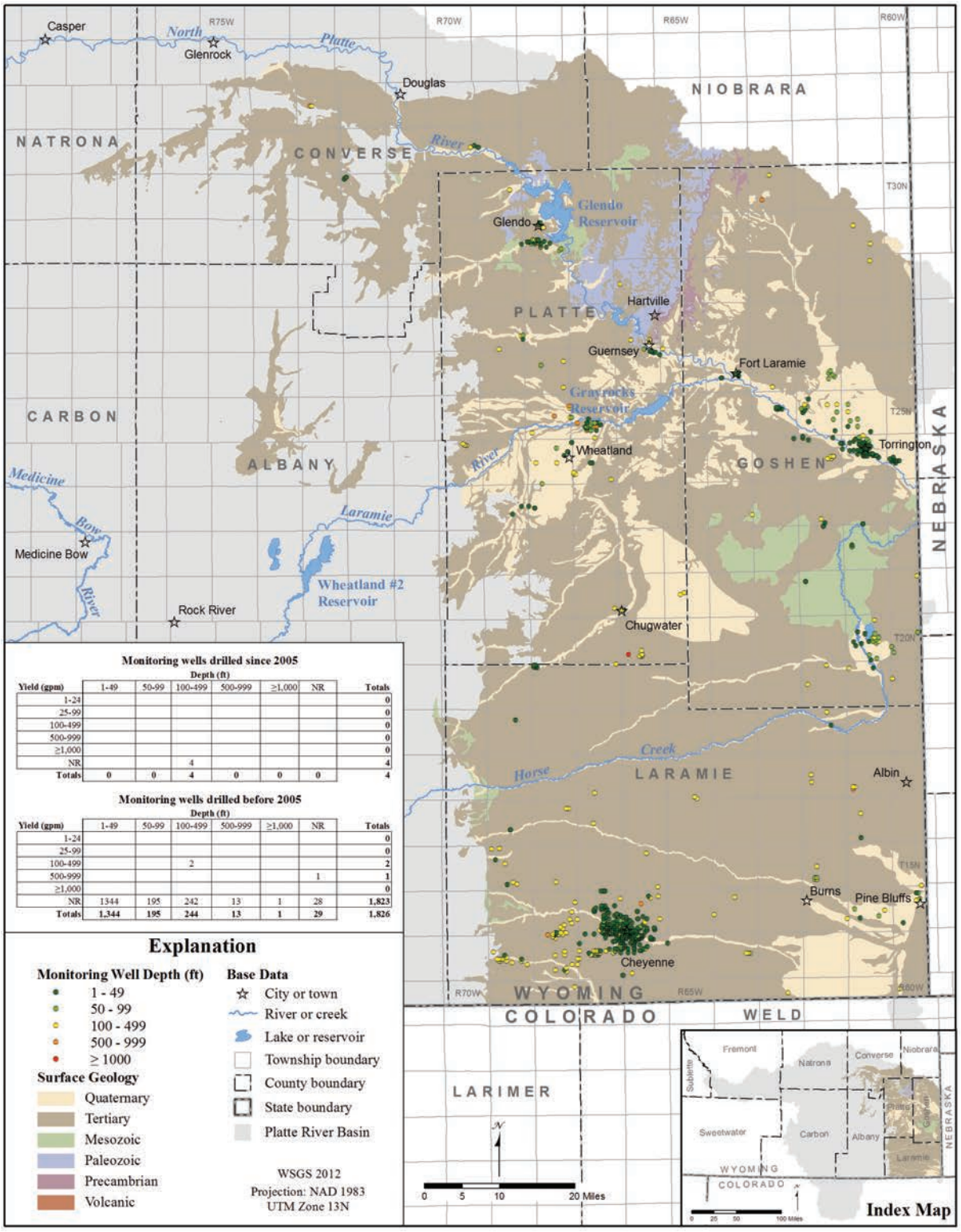
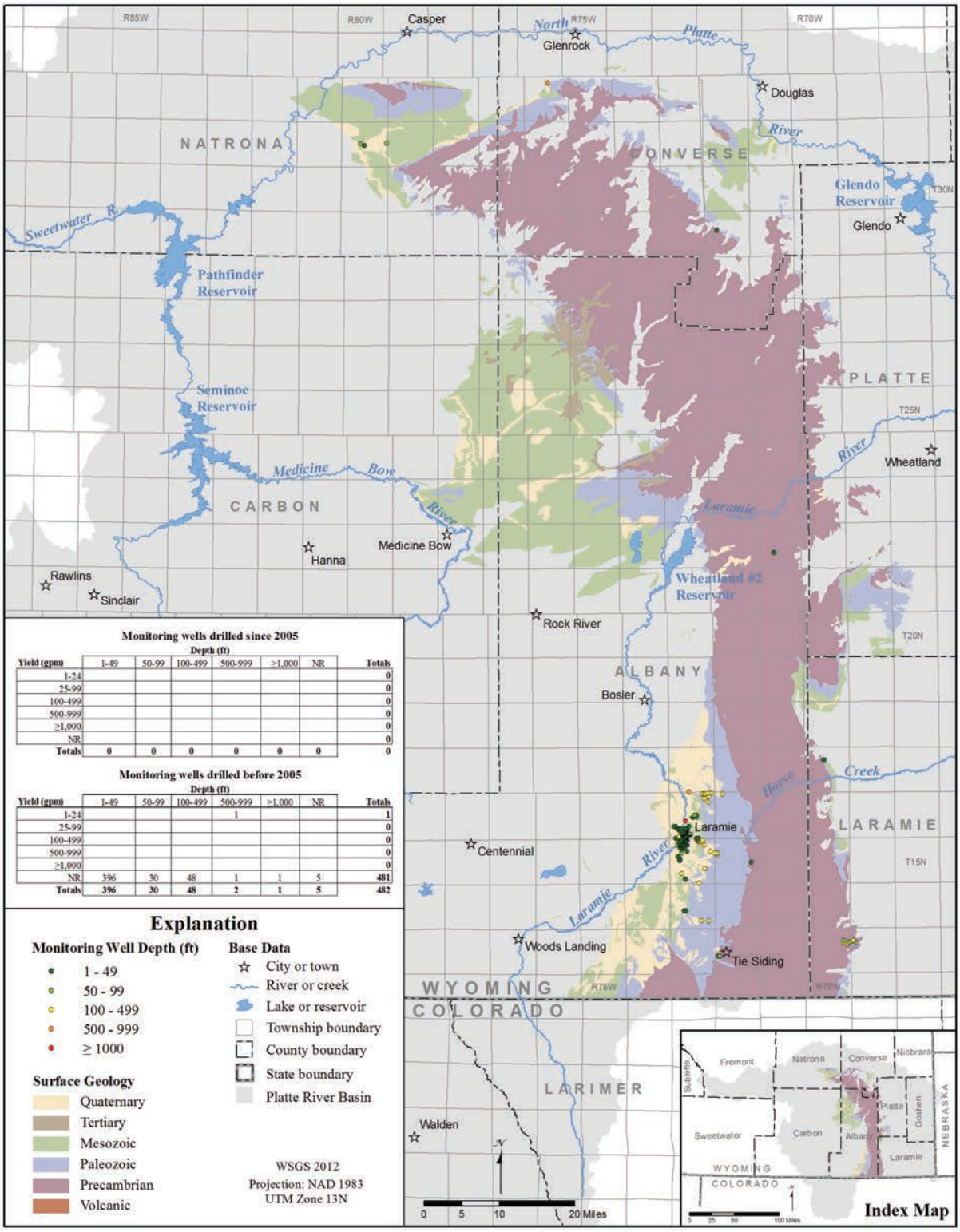


Figure 8-26. Wyoming SEO permitted and drilled monitoring wells in the Denver Basin and Hartville Uplift Subregion.



Monitoring wells drilled since 2005							
	Depth (ft)						
Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR							0
Totals	0	0	0	0	0	0	0

Monitoring wells drilled before 2005							
	Depth (ft)						
Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24				1			1
25-99							0
100-499							0
500-999							0
≥1,000							0
NR	396	30	48	1	1	5	481
Totals	396	30	48	2	1	5	482

Figure 8-27. Wyoming SEO permitted and drilled monitoring wells in the Laramie Mountains and Central Uplifts Subregion.

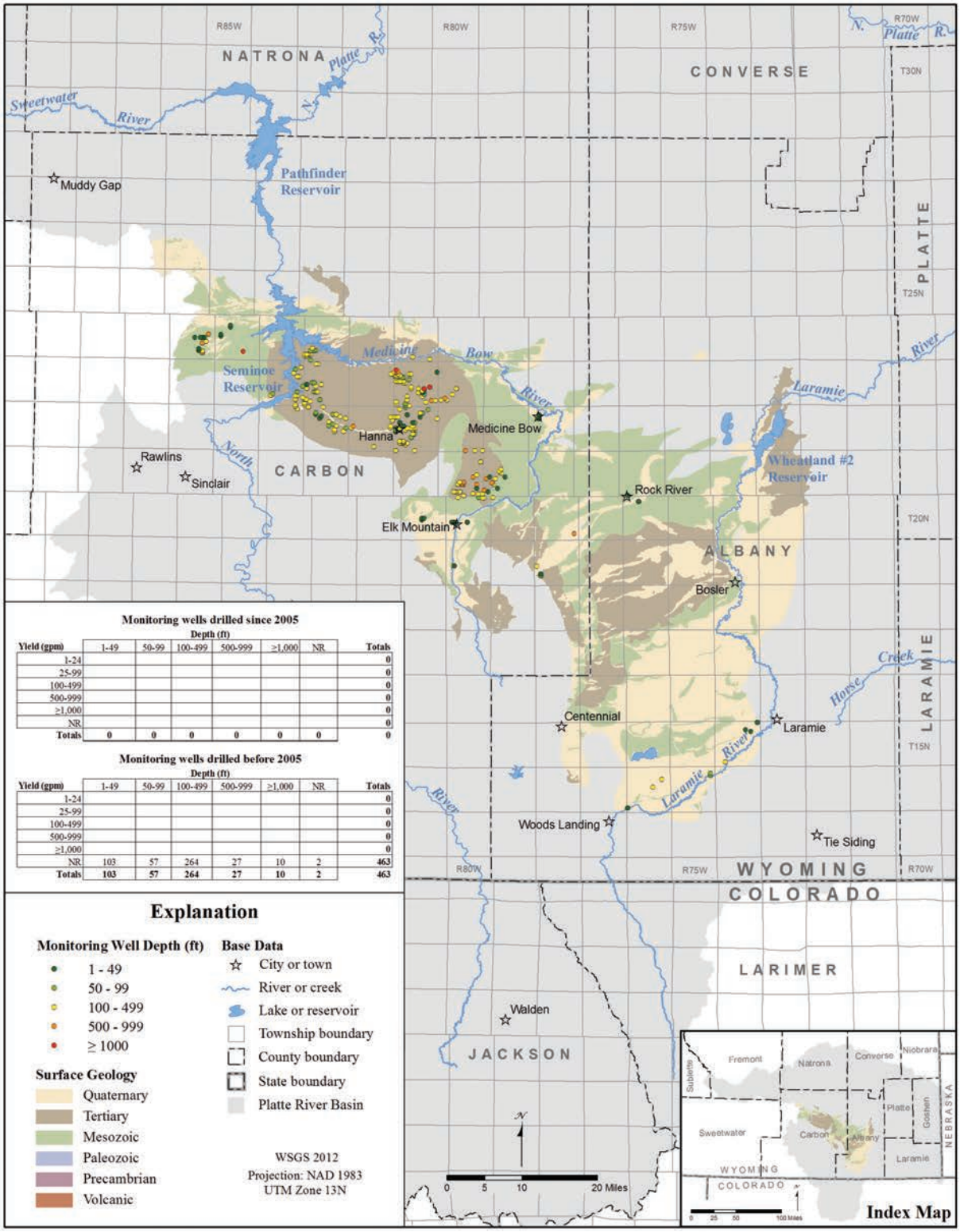
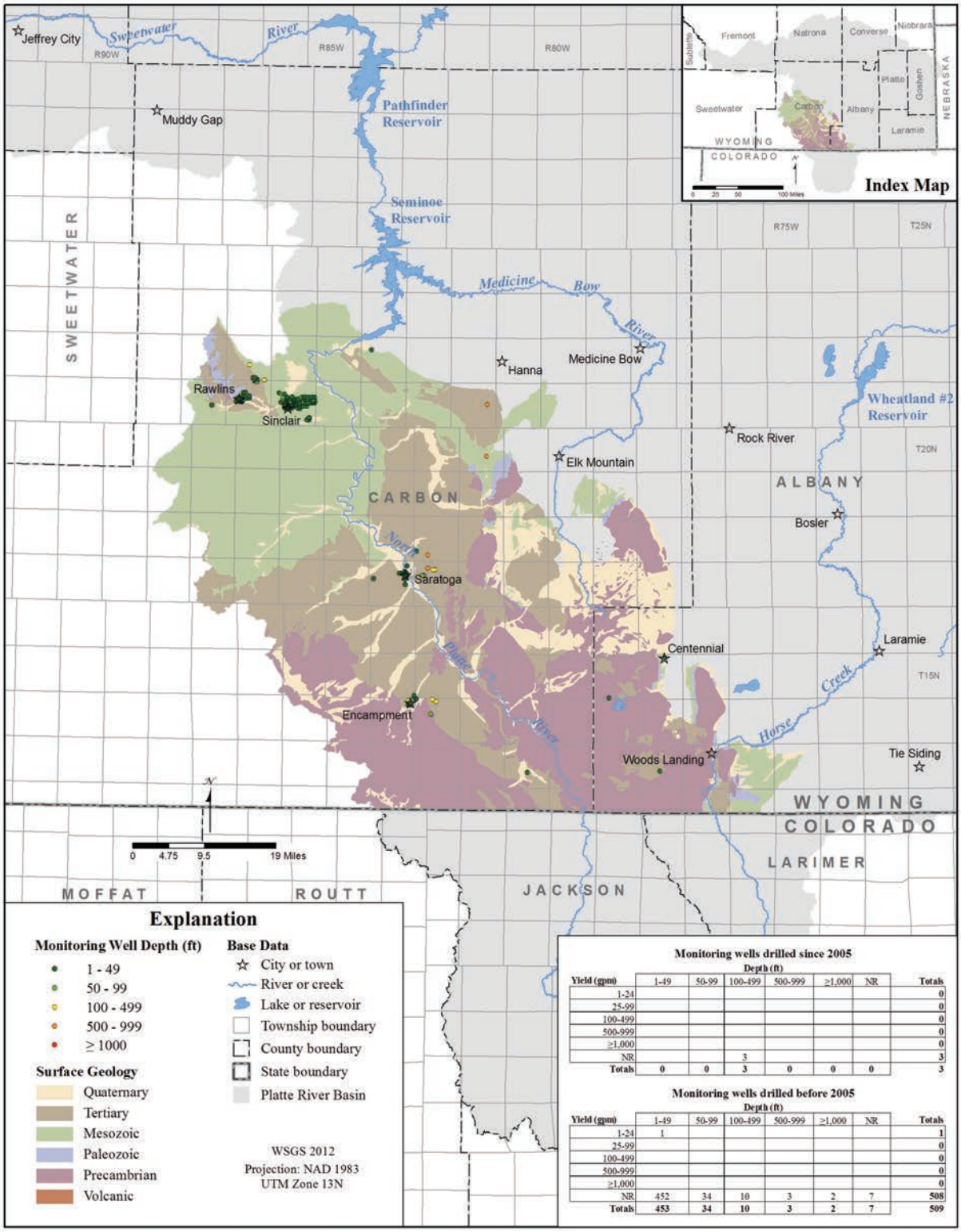


Figure 8-28. Wyoming SEO permitted and drilled monitoring wells in the Laramie and Hanna Basins Subregion.



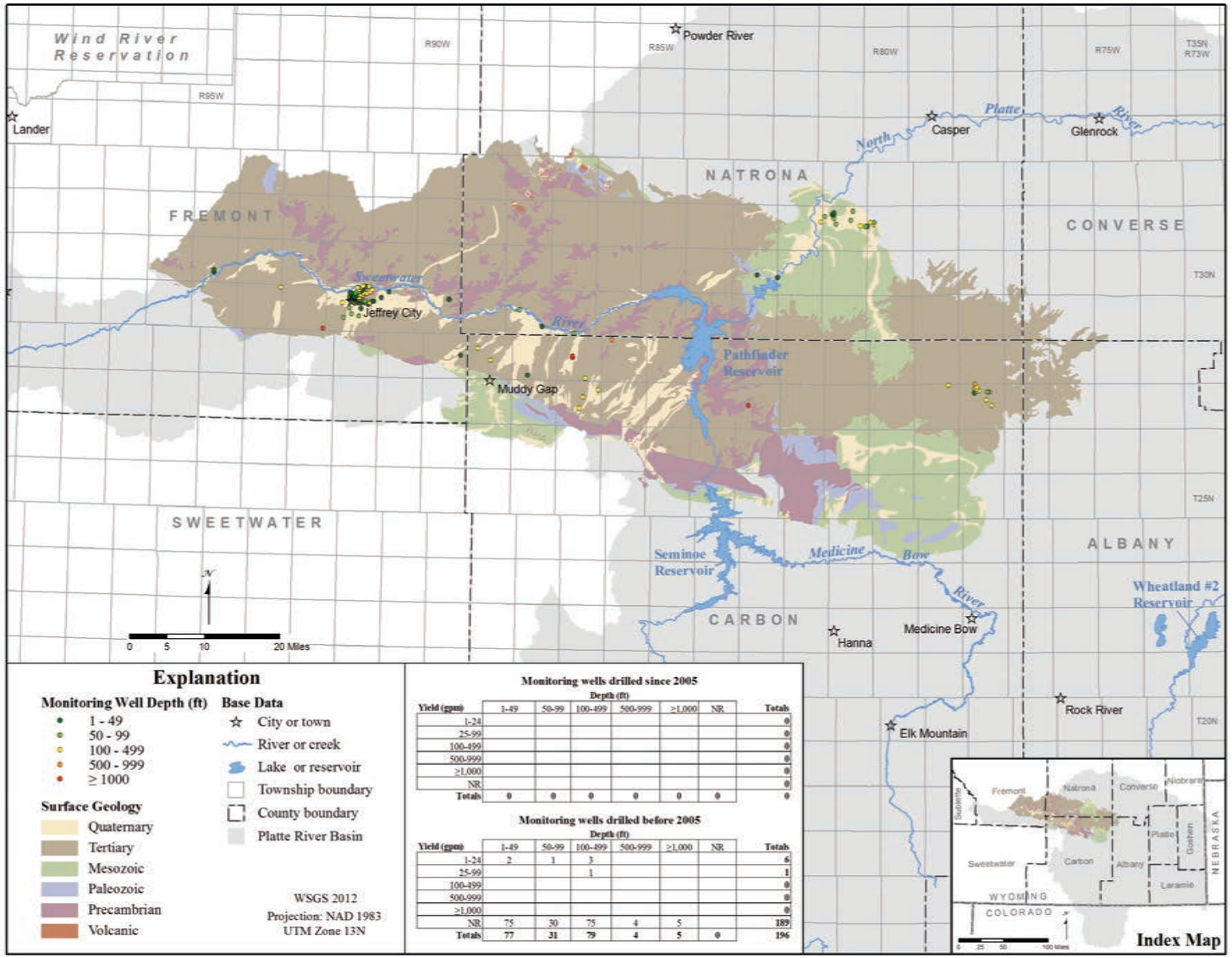
Monitoring wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR			3				3
Totals	**0**	**0**	**3**	**0**	**0**	**0**	**3**

Monitoring wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1						1
25-99							0
100-499							0
500-999							0
≥1,000							0
NR	452	34	10	3	2	7	508
Totals	**453**	**34**	**10**	**3**	**2**	**7**	**509**

Figure 8-29. Wyoming SEO permitted and drilled monitoring wells in the Medicine Bow Mountains and Sierra Madre Subregion.



Monitoring wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
>1,000							0
NR							0
Totals	0	0	0	0	0	0	0

Monitoring wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	>1,000	NR	Totals
1-24	2	1	3				6
25-99			1				1
100-499							0
500-999							0
>1,000							0
NR	75	30	75	4	5		189
Totals	77	31	79	4	5	0	196

Figure 8-30. Wyoming SEO permitted and drilled monitoring wells in the Granite Mountains and Shirley Basin Subregion.

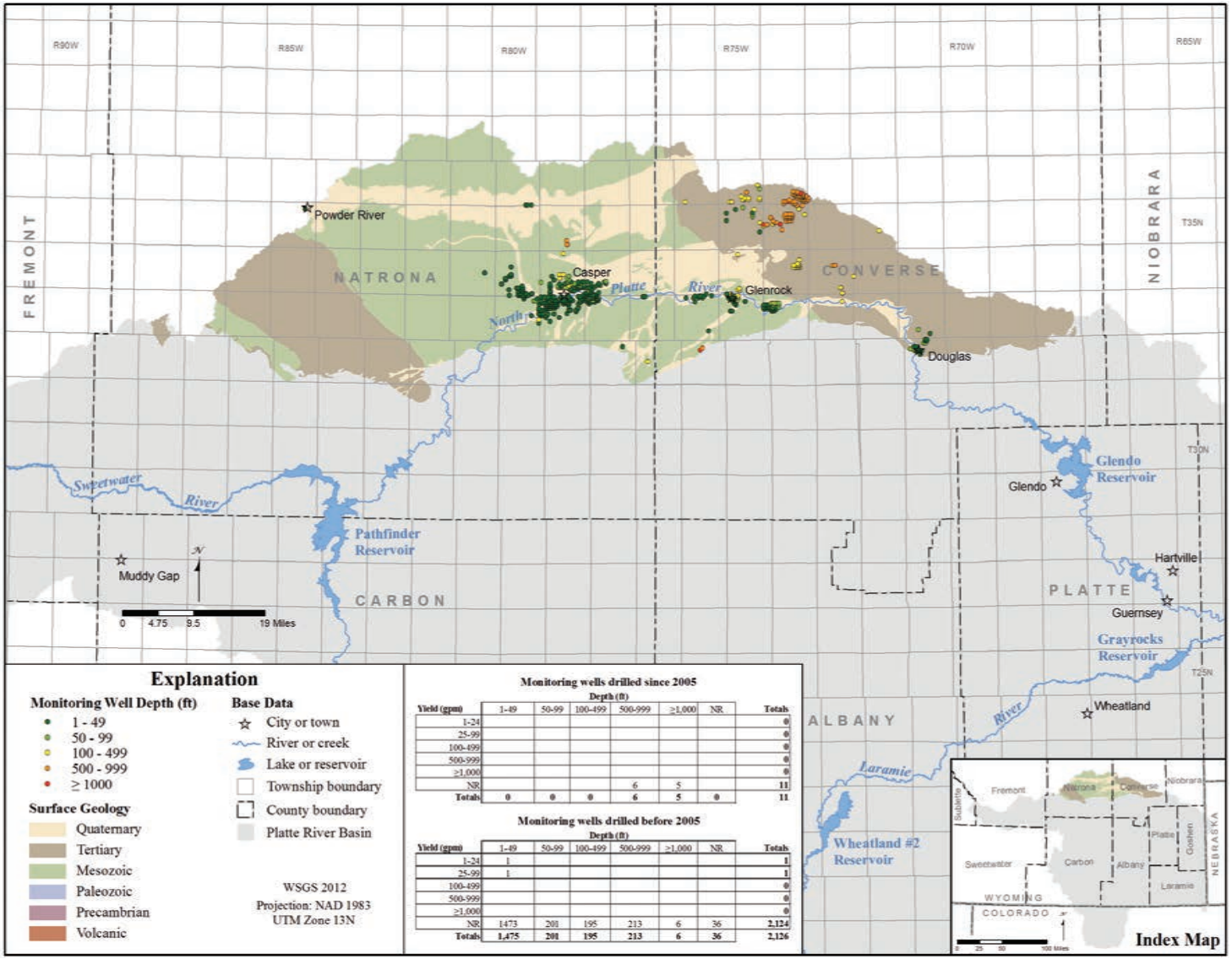
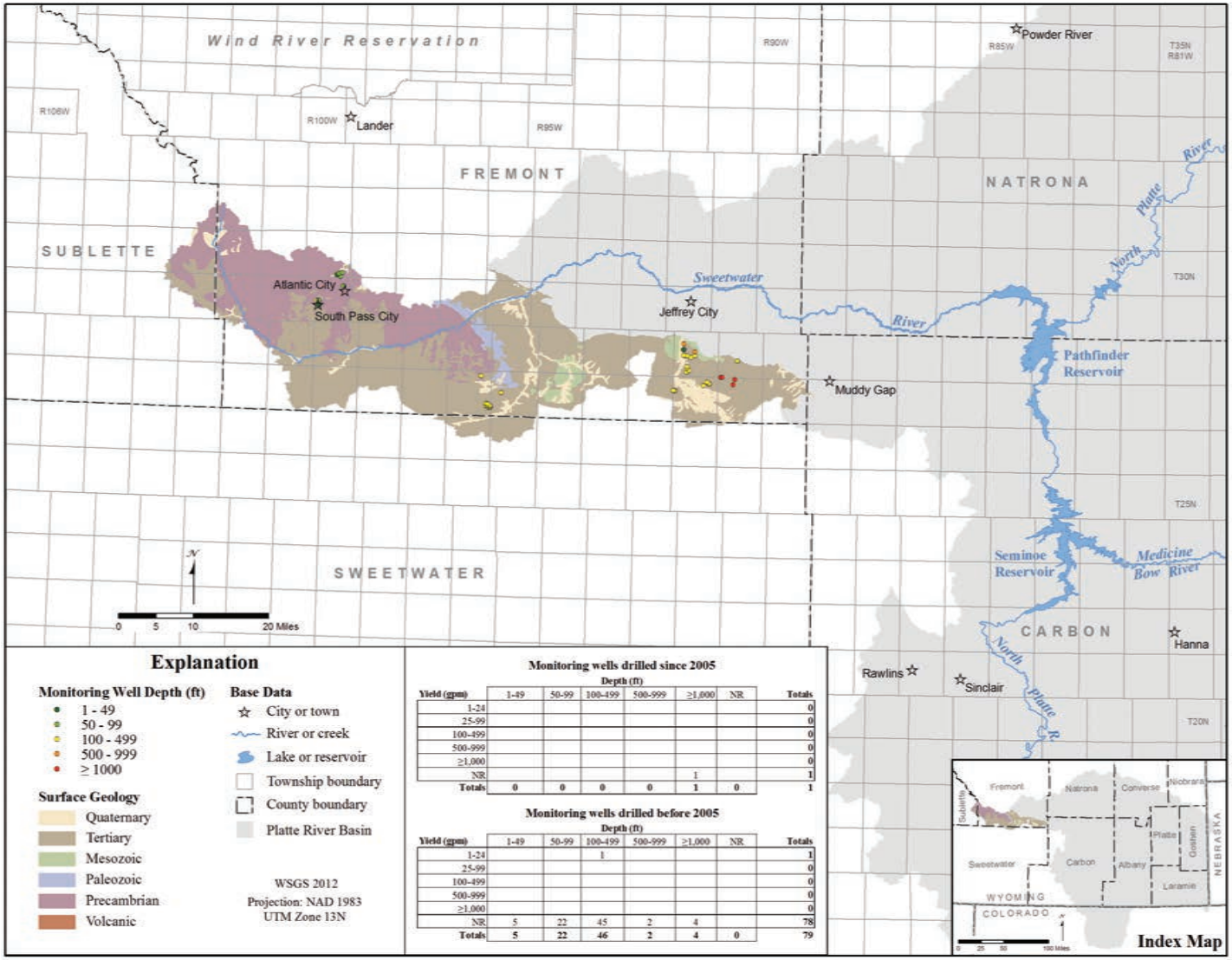


Figure 8-31. Wyoming SEO permitted and drilled monitoring wells in the Casper Arch, Wind River and Powder River Basins Subregion.



Monitoring wells drilled since 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR					1		1
Totals	**0**	**0**	**0**	**0**	**1**	**0**	**1**

Monitoring wells drilled before 2005

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24			1				1
25-99							0
100-499							0
500-999							0
≥1,000							0
NR	5	22	45	2	4		78
Totals	**5**	**22**	**46**	**2**	**4**	**0**	**79**

Figure 8-32. Wyoming SEO permitted and drilled monitoring wells in the Wind River Mountains and Great Divide Basin Subregion.

permitted yield for other uses. The SEO required permits for monitoring wells of 4 inches or less in diameter only through 2004; therefore, the data for these permits is incomplete.

Figures 8-25 through 8-32 shows the distribution of likely drilled SEO monitoring well permits in the Platte River Basin and permits issued before and after January 2005. Most monitoring wells are located near population centers, areas with industrial facilities, and along rivers and other large surface drainages, where facilities that require groundwater monitoring are concentrated. The depth vs. yield tables on **Figure 8-25** show that while permits have been issued for all depth categories, by far the largest number were issued for depths of 0 to 50 feet reflecting monitoring of the shallow water-table aquifers that are most susceptible to contamination. Although, recorded depths are available for most monitoring wells in the database, few well permits include recorded yield data. Very few of the wells were permitted after 2005; however, as discussed above, this number is probably understated, per the 2004 SEO policy change.

8.4.4.8 Miscellaneous-use permits

Table 8-6 lists the number of SEO groundwater permits for miscellaneous use in the Platte River Basin at 4,140. **Tables 8-6 and 8-7** list 678 SEO groundwater permits for test wells, 130 SEO permits for other wells and 14 CDWR permits for other wells in the Platte River Basin. Test wells are generally used for aquifer testing to determine aquifer characteristics. Information on specific miscellaneous use and test wells may be found in some permit applications available on-line. However, developing detailed information for specific miscellaneous use and test wells was beyond the scope of this study.

Figure 8-33 shows the distribution of likely drilled wells permitted for miscellaneous use and test wells in the Platte River Basin, and permits issued before and after January 2005. Miscellaneous-use and test wells are located throughout the Platte River Basin in population centers, in mineral development areas, in rural areas, and generally along rivers and larger surface drainages. The depth vs. yield tables on **Figure 8-33** show that the largest number of groundwater permits has been issued for depths up to 500 feet and for yields of 0 to 99 gpm for both total permits and permits issued since 2005. More than one-quarter of all permits for miscellaneous use and test wells have been issued since 2000. More than one-third of these permits are coded or have no recorded depth.

8.4.4.9 Hydrothermal use

Section 4.7 discusses the limited development of hydrothermal resources, and **Figure 4-21** shows areas of anomalously high heat flow that may provide opportunities for the future development of hydrothermal resources in the Platte River Basin. The SEO database does not include hydrothermal development as a primary use category, but in some cases it may be identified as a sub-category in individual permit applications for miscellaneous use wells. Determination of the number of wells and springs permitted for hydrothermal use was beyond the scope of this study. The Platte River Basin has no potential for high-grade geothermal energy development.

8.5 Groundwater interference/interconnection with surface water

The potential for interference between wells and well fields located within areas that exhibit historically high levels of drawdown and interconnections between groundwater and surface water must be considered when assessing the historic, current, and future use of groundwater in the Platte River Basin. Generally, these issues are addressed within the state's institutional and regulatory framework for groundwater development **(Chapter 1)**. Additional regulation is provided by the three SEO established groundwater control areas in Platte, Laramie and Goshen Counties, the Modified North Platte Decree (Decree) and Platte River Recovery Implementation Program (PRRIP). The locations of areas where groundwater has been determined to be not hydrologically connected to the North Platte River and groundwater permit applications would not be subject to the Decree and PRRIP, and the three SEO Groundwater Control Areas, where groundwater development is otherwise restricted, are shown on **Figure 9-1.**

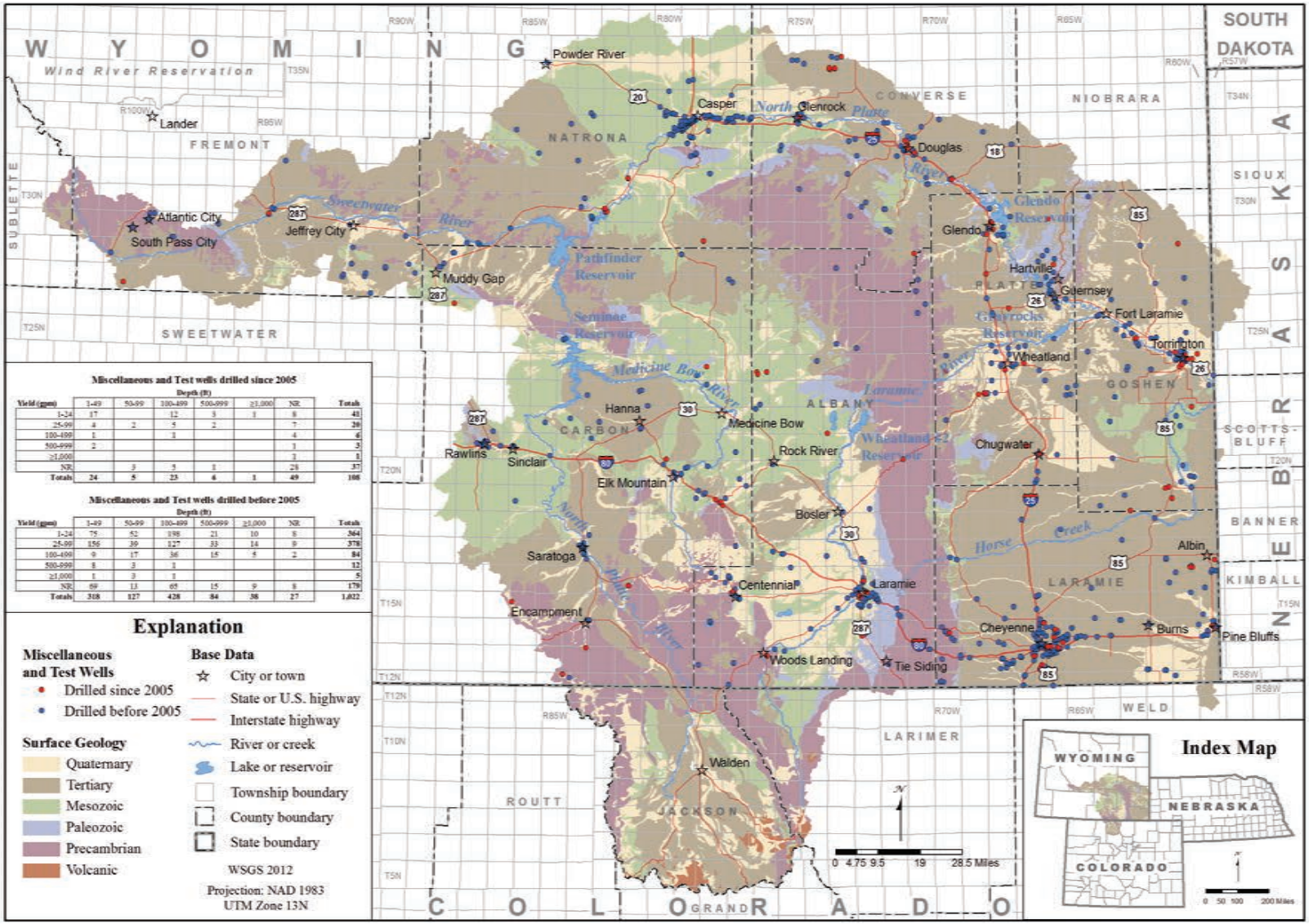


Figure 8-33. Wyoming SEO permitted and drilled miscellaneous and test wells.

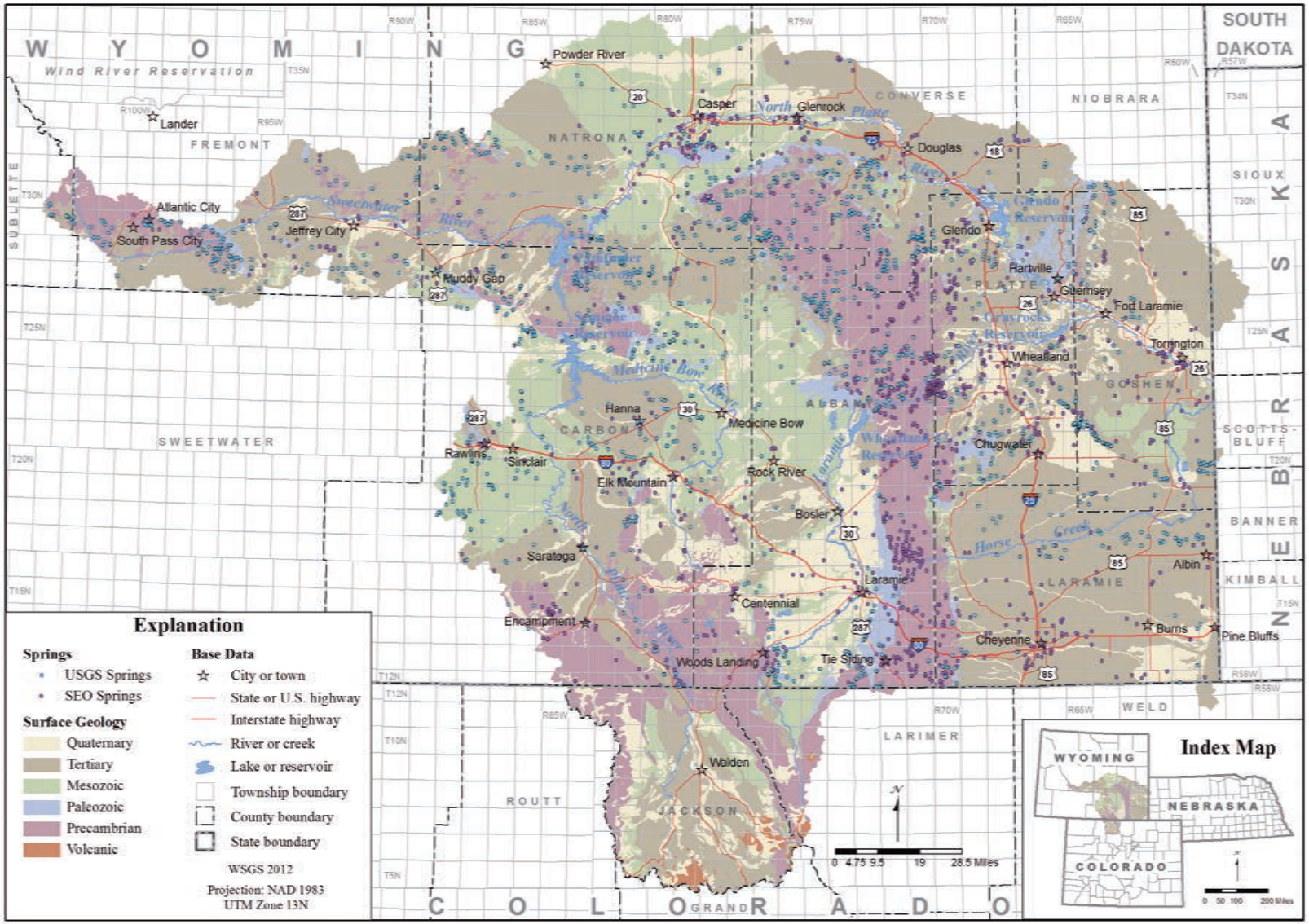


Figure 8-33. Wyoming SEO permitted springs and USGS mapped springs.

8.5.1 Interference between wells

According to Wyoming statutes, a "control area" can be designated by the Board of Control on the recommendation of the State Engineer for any of the following reasons:

- The use of underground water is approaching a use equal to the current recharge rate.
- Groundwater levels are declining or have declined extensively.
- Conflicts between users are occurring or are foreseeable.
- The waste of water is occurring or may occur.
- Other conditions exist or may arise that require regulation for the protection of the public interest.

Three groundwater control areas (also referred to as management districts) have been established by the State Board of Control in the Platte River Basin in response to historical and ongoing declining groundwater levels associated with heavy groundwater withdrawals, primarily for irrigation. Within a control area, all permit applications for new wells requesting a yield of more than 25 gpm, or petitions to change an existing well use must be reviewed by a 5-member Advisory Board, including a public notification process. The Advisory Board then makes recommendations to the State Engineer and Board of Control concerning the specific application or petition. Additional information about Control Area administration and procedures can be found online at https://sites.google.com/a/wyo.gov/seo/ground-water/groundwater-control-areas-advisory-boards.

The locations of the control areas are shown on **Figure 9-1.** Note that all of the Platte County Management District and parts of the Laramie County and Prairie Center Control Areas fall within the North Platte River Basin and may be subject to overlapping restrictions contained within the Decree and/or the PRRIP. The previous Water Plan for the Platte River Basin (WWC Engineering, Inc., and others, 2007) provided the following background on the three control areas in the Platte River Basin:

The **Prairie Center Control Area** is located in northeastern Goshen County within the Guernsey to State Line drainage subbasin. The Prairie Center Control Area was established on December 2, 1977 due to declining groundwater levels in the Quaternary and Upper Tertiary Aquifer Systems. An area within Niobrara County was removed from the Control Area in March 1979. Approximately one third of the control area in the northeast corner lies outside of the North Platte River drainage. The remainder of the control area falls within an area where groundwater is designated as "not-hydrologically connected" by the modified North Platte Decree; therefore there would be minimal overlapping restrictions on groundwater development between the control area and the Decree/PRRIP.

The **Platte County Control Area** is located in central Platte County within the Pathfinder to Guernsey and Lower Laramie drainage subbasins. The Platte County Control Area was established on February 1, 1982, due to development in the Wheatland-Dwyer Junction area of Platte County. Some of the control area has been designated as "not hydrologically connected" for Decree and PRRIP purposes; therefore, some areas are subject to overlapping restrictions on groundwater development between the management district and the Decree/PRRIP.

The **Laramie County Control Area** is located in eastern Laramie County within South Platte and Horse Creek drainage subbasins. The Laramie County Control Area was established on September 2, 1981, due to declining groundwater levels in the Quaternary and Late Tertiary aquifers. The northern third of the control area lies within the North Platte River drainage, and the rest of the control area is in the South Platte River Basin. Some of the control area within the North Platte River Basin falls outside the "not hydrologically connected" areas designated by the Decree and is subject to overlapping restrictions on groundwater development.

8.5.2 Interconnection between groundwater and surface water

Surface flows are subject to strict water rights, and conflicts occur where groundwater extraction affects surface flow. The water of the

North Platte River has been fully appropriated for several years, and the federal courts have recognized that withdrawals of hydrologically connected groundwater impact river flows (WWC Engineering, Inc., and others, 2007) and encroach upon priority water rights. Tributary interconnection between groundwater and surface water is a prominent water-rights issue in the Platte River Basin. As discussed briefly in **Chapter 1**, the future development of groundwater is significantly constrained by both the 2001 Modified North Platte Decree and the Platte River Recovery Implementation Program (PRRIP).

Under the Decree, criteria were developed for identifying areas where groundwater is not hydrologically connected to the North Platte River for purposes of Decree administration. Subsequently, SEO developed maps that delineate these areas, informally known as the "green areas. (**Figure 9.1)** Green areas primarily affect current uses and future development of groundwater for irrigation.

The PRRIP was developed to address issues under the Endangered Species Act (ESA) related to the improvement and conservation of water-dependent habitat of four threatened and endangered species populations located along the Platte River in central Nebraska, and to allow current use and future development of water resources in the Platte River Basin to proceed without additional ESA requirements related to these threatened and endangered species. Because the use of hydrologically connected groundwater can deplete surface water flows and impact habitats of concern, the parties to the PRRIP adopted the hydrological connection criteria from the Decree.

The Decree defines a hydrologically connected groundwater well as a well: "*. . . that is so located and constructed that if water were intentionally withdrawn by the well continuously for 40 years, the cumulative stream depletion would be greater than or equal to 28% of the total groundwater withdrawn by that well."* In general, the deeper and more distant an aquifer is from surface water, the less potential there is for interconnection with surface water. The potential for stream depletion due to interconnection between groundwater and surface water is highest where alluvial aquifers are associated with active streams.

Three maps applying the Decree criteria for hydrological connection were developed for North Platte River subbasins: 1) above Alcova, 2) Alcova to Guernsey, and 3) the Lower Laramie basins. The Upper Laramie, Horse Creek, and Guernsey to State Line drainage subbasin maps were subsequently developed for use under the PRRIP. The maps applying the "hydrologically connected" criteria, and additional information on development of the maps, can be found on the SEO web-site:
https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/platte-river-basin.

Appendix D (Hinckley, 2011 - https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/platte-river-basin) describes the background and history of the Decree and the PRRIP, and the criteria for determining whether groundwater is hydrologically connected to surface water. Groundwater prospects may be developed in zones located outside of green areas if a site-specific hydrogeologic investigation, consistent with the criteria outlined in the Decree, provides substantial evidence that ground and surface waters are not connected. The evidence required for such a determination consists of published reports, academic theses, peer-reviewed journal articles, borehole drilling logs, geophysical logs, publicly available well data, geospatial information and numerical groundwater models. Investigations are submitted to the SEO and, in some cases, to the North Platte Decree Committee for review and approval. A copy of the *Decree* can be found at:

https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/platte-river-basin.

Finally, at SEO's discretion, depletions of flow in the North Platte River associated with withdrawals of hydrologically connected groundwater may be replaced, or mitigated, from other sources, rather than regulating the use or development of groundwater (WWC Engineering, Inc., and others, 2007). Trihydro Corporation (Trihydro Corporation, 2007b) investigated the cost and feasibility of developing several potential new groundwater prospects in "green areas" to mitigate surface water depletions in the North Platte River **(Figure 9-1).** Subsequently, a groundwater exploration program was conducted

for the WWDC at the most promising site, the Split Rock Prospect near Muddy Gap. A copy of the report for the Split Rock Prospect is available at: http://library.wrds.uwyo.edu/wwdcrept/North_Platte/North_Platte-Assessment_Split_Rock_GW_Hydrologic_Casper_Pipeline-Executive_Summary-2008.html.

Chapter 9

Looking to the Future

Karl Taboga, Paul Taucher, Keith Clarey, Lisa Lindemann

The purpose of this chapter is to discuss future water use opportunities in the Platte River Basin. This issue was thoroughly examined in the 2006 Platte River Basin Water Plan (Trihydro Corporation and others, 2006a). Technical Memorandum 5.1 (Trihydro Corporation, 2005j) examined the hydrogeologic, political, financial and regulatory factors that limit future water development projects in the basin. Technical Memorandum 5.2 (Trihydro Corporation, 2005g) discussed 19 specific water use opportunities in detail. This update will present brief reviews of a select few of these previously discussed opportunities as well as provide brief descriptions of recent Wyoming Water Development Commission (WWDC) and U.S. Geological Survey (USGS) water development studies completed after the 2006 Platte River Basin Water Plan. This approach provides the most current information available about the future focus and direction of Platte River Basin groundwater development projects.

The discussions of technical concepts and Laramide geology previously covered in this study provide the background needed to understand the practical considerations that shape the conceptualization, design and successful completion of a water resource development project. **Chapter 5** opened with the definition of several elementary hydrogeologic concepts that are crucial to understanding basic groundwater science. **Section 5.1.3** introduced the dynamics of groundwater recharge, discharge and flow and hydrogeologic settings that are characteristic of Laramide-age structural basins. Future groundwater development in the Platte River drainage is not only physically limited by Laramide basin hydrogeology but is also legally bound by the judicial restrictions imposed by the 2001 Modified North Platte River Decree and the Platte River Recovery Implementation Program (PRRIP); the hydrogeologic principles of these policies are summarized in **Appendix D**. Specific groundwater development projects are discussed below in **Section 9.1**, and recommendations for future updates of this Groundwater Determination Technical Memorandum in **Section 9.2**.

Additional supporting information for the project assessments contained in this chapter can be found in several previous chapters of this study:

- Hydrogeology (**Chapters 5, 6, and 7, Figure 7.2 and Plates J, K, M, S, T, U, X**)
- Groundwater chemical characteristics (**Chapter 7 and Appendices E,F,G,H**)
- Recent and historic development patterns specified by beneficial use, obtained from the State Engineer's Office E-Permit Database (**Chapter 8**)
- Studies published by the USGS (**Chapter 7**) and Wyoming Water Development Commission (**Appendix B**) that examine the development potential of specific aquifers
- The 2006 Water Plan for the Platte River Basin (Trihydro Corporation and others, 2006a) and associated Technical Memoranda, as well as the 2007 State Water Plan (WWC Engineering and others, 2007), identify potential groundwater development projects considered prior to the completion dates of those studies. Many of the opportunities examined in those publications may be under current development or will become more viable in the future as financial factors and technological improvements allow.
- The Water Resources Data System Library, specifically the WWDC Projects and Studies Web page, contains hundreds of water development reports for projects completed over the last 40 years for localities throughout Wyoming.

In this chapter, only development projects that are designed with the primary objective of producing fresh groundwater suited to their intended beneficial uses are discussed. Projects which may produce groundwater as a value added byproduct of other activities, such as oil and gas production or in-situ mineral extraction, are not considered.

9.1 Issues affecting future groundwater development (Trihydro Corporation and others, 2006a)

- Water availability –A groundwater resource must meet the water quality and production volumes of the proposed beneficial use(s) and be legally, economically and physically

available. In the Platte River Basin, groundwater availability is controlled by the hydrogeology of the Laramide-age structural basins as well as the Modified North Platte Decree and the PRRIP (see below).

- Funding – Groundwater development projects are expensive and most Wyoming municipalities do not have the funds required to plan, carry out and complete development programs. Funding for these projects, therefore, has to be obtained from governmental agencies. The primary water development funding agencies in Wyoming are the WWDC, Wyoming Department of Environmental Quality (DEQ) and the U.S. Department of Agriculture.
- Stakeholder involvement – The successful completion of any groundwater project requires the involvement of the stakeholders who have interests in the development or preservation of the water resource. Stakeholders include current and future water users, landowners, business representatives, attorneys, scientists, engineers, environmentalist groups, sportsmen, holders of competing water rights, municipal, state and federal regulatory agencies and others. Stakeholder support for or opposition to a water development project depends on the nature, benefits, costs and perceived impacts of the particular project. The project will likely incur substantial cost increases and time delays if legal challenges are filed by stakeholders opposed to development.
- Court decrees - The 1945 North Platte River Decree, the 2001 Modified North Platte River Decree, and the Laramie River Decree have significantly affected water use in the Platte River Basin. The provisions of these decrees are primarily administered by the SEO.
- Platte River Recovery Implementation Program (PRRIP) – The SEO Interstate Streams website describes the PRRIP as follows: "On January 1, 2007, the State of Wyoming entered into the Platte River Recovery Implementation Program (PRRIP) with the U.S. Department of the Interior and the States of Colorado and Nebraska. The purpose of the PRRIP is to ensure continued use and development of Wyoming's water in the Platte River basin while maintaining compliance under the Endangered Species Act (ESA). To define the water use covered by the PRRIP, Wyoming's Depletions Plan was developed. In the plan, water use covered by the PRRIP is based on a depletion baseline that occurred from 1992 through 1996. Under the PRRIP, Wyoming must annually measure and compare its current water use (depletions) against the thresholds for depletions that were quantified for that 1992-1996 period." SEO contact information for the Interstate Streams Program and links to other documents related to the PRRIP can be found online at: Platte River Basin - Wyoming State Engineer's Office.
- Water quality – The successful completion of a groundwater development project depends on whether the quality of the water produced from the targeted resource meets the requirements of the intended beneficial use(s). State and federal laws may mandate water quality requirements for certain beneficial uses or may, alternately, be used as a reference measure for others. For example, the National Primary Drinking Water Regulations **(Table 5-2)** established by the Environmental Protection Agency (EPA) under provisions of the Safe Drinking Water Act are legally enforceable standards for public water systems (PWS) but do not regulate water quality in private groundwater wells that serve less than 25 people. Still, water quality in smaller private wells is frequently evaluated in comparison to the Maximum Contaminant Levels (MCLs) contained in the EPA regulations.
- Environmental regulation – Water development projects in Wyoming are also subject to regulation under the provisions of state and federal environmental laws which include:
  - Wyoming Environmental Quality Act – the principal state environmental law

that created the Wyoming Department of Environmental Quality, repealed the state's existing environmental laws (in 1973) and replaced them with the provisions of the new act.

- Endangered Species Act – a federal environmental law designed to protect imperiled species of plants and animals from extinction. The ESA is administered under the Endangered Species Program of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration (NOAA).
- National Environmental Policy Act – the main federal law that established national environmental policy. It requires federal agencies in the executive branch to write environmental impact statements (EISs) and environmental assessments (EAs) that examine anticipated impacts to the environment resulting from proposed federal agency actions.
- Clean Water Act – the principal federal law that governs pollution in the nation's surface waters. The CWA does not regulate groundwater pollution directly. The Water Quality Division of DEQ regulates the discharge of pollutants to surface waters under the CWA.
- Safe Drinking Water Act – the primary federal law that ensures safe drinking water supplies for the public. The SDWA covers public water supplies but does not apply to private wells that serve less than 25 people. The EPA administers and enforces provisions of the SDWA.

9.1.1 Groundwater development potential in areas of the North Platte River Basin that fall within the jurisdiction of the 2001 Modified North Platte River Decree or the PRRIP

Maps have been developed of areas determined not to be "hydrologically connected" under the criteria of the Modified North Platte Decree (Fig. 9-1). Wells located within these areas are considered to have no hydrologic connection at any depth to the North Platte River or its perennial tributaries for purposes of Decree and PRRIP administration. Groundwater volumes extracted from wells located within the designated areas are not subject to the requirements of these programs. These designations of "not connected" do not affect the appropriation of surface water."

The potential for future development of groundwater resources in the North Platte River drainage basin must be viewed within the context of the "not-connected" area maps because the procedure with which the SEO reviews and approves the application for a Permit to Appropriate Ground Water is determined by the location of the proposed development. Applications for wells located within these areas are typically approved by the SEO whereas applications for groundwater development outside of the "not connected" areas are usually not approved. Wells that fall outside of these areas may or may not be hydrologically connected and may require a site specific hydrogeologic study to determine the presence and degree of connection to the Platte River and its tributaries.

Appendix B contains a chronological summary of groundwater development related projects sponsored by the WWDC in the Platte River Basin since 1973. Information contained in the project reports from many of these studies was used to describe, in detail, the physical and chemical characteristics of the basin's hydrogeologic units in **Chapter 7**. **Appendix B** summarizes the following groundwater development information for WWDC projects in the Platte River Basin:

- References to the study(s) – full citations are included in the References
- Location, including as appropriate: town, county, rural area, irrigation district, well site, etc.
- Aquifers involved in the study
- Project descriptions of development potential of area(s) and aquifer(s) and development drilling project(s)
- Summary of results
- Current project status

9.1.2 Future water use opportunities (Trihydro Corporation, 2005g)

The previous Platte River Basin Water Plan (Trihydro Corporation and others, 2006a)

provides a detailed discussion of future water use opportunities in Technical Memorandum 5.2 (Trihydro Corporation, 2005g). The opportunities, discussed, were considered with the intention that their implementation would result in expanded water supplies that could be used to meet current and future water demands. Technical Memorandum 5.2 examined both structural and non-structural opportunities. Structural opportunities are projects that involve the design and construction of new water storage and conveyance infrastructure or the modification and improvement of existing infrastructure to include new or upgraded groundwater development, enlarging reservoirs, trans-basin diversion programs or improving existing water distribution systems. Non-structural opportunities do not require modifications to infrastructure but involve programmatic changes in water use and management such as water conservation programs, improvements in efficiency-of–use, water-banking, and improved reservoir operation.

Trihydro submitted an initial draft of water use opportunities to WWDC. Subsequently, a final list of future water use opportunities was determined following WWDC and Platte River Basin Advisory Group reviews and comments (see Trihydro Corporation, 2005g, pp. 5.2-4 – 5.2-5). Trihydro evaluated the opportunities contained in the finalized list on the basis of nine considerations that generally reflect the issues that affect groundwater development, discussed above in **Section 9.1** of this report:

1. Pertinent water use sectors
2. Water availability
3. Technical factors
4. Economic factors
5. Environmental factors
6. Legal and institutional factors
7. Public acceptance
8. Water quality
9. Ability to satisfy multiple demands

Beyond the brief review contained in this section, Technical Memorandum 5.2 (Trihydro Corporation, 2005g) contains a detailed description of the methodology used to select the water use opportunities to be examined as well as complete discussions of the particular structural and nonstructural water use opportunities. This report examines two structural opportunities that have generated particular interest at WWDC (K. Clarey, oral commun.); new groundwater resource development and regionalization of public water supply systems.

9.1.3 Potential new groundwater development prospects

Trihydro Corporation (2007b) conducted the North Platte River Groundwater Assessment Study (NPRGAS) for WWDC during 2002 - 2004 (revised 2007) to identify groundwater resources that were determined to be "non-hydrologically connected" to the surface waters of the North Platte River. Specifically, the basin wide groundwater evaluation sought to identify high yield aquifers that could produce 500 to 1,000 gpm per constructed well. Initially, Trihydro conducted a review of available hydrogeologic data and identified 73 groundwater prospects (Figure 2, Trihydro Corporation (2007b)) in the Platte River Basin. Subsequent joint evaluations by Trihydro, Lidstone, the SEO, WWDC and the Wyoming Attorney General's Office reduced the list of prospects first to 28 and then to 10.

The stated purpose of the NPRGAS program was to evaluate the feasibility and associated costs of developing new groundwater resources that could supply from 5,500 to 10,000 acre-feet of augmentation water per year. Although, the produced volumes were intended to offset Wyoming depletions of the North Platte River, the aquifer information provided in the NPRGAS report can readily be adapted to evaluate groundwater targets in new development projects. An overview of general groundwater development potential is provided in the NPRGAS report for major regional aquifer systems that correspond to the age-grouped aquifer systems developed in Chapter 6 and Plate II of this report. Results of the regional aquifer system evaluations are summarized in **Table 9-1**.

Virtually all aquifers and some confining units in the Platte River Basin have some physical potential for development, depending on the requirements for quantity and quality called for

Table 9-1: Generalized groundwater development potential for major regional aquifer systems in the Platte River Basin (modified from Trihydro Corporation, 2007b).

	System	Location	Well yields	Major aquifers	General potential for new development
	Alluvial	Throughout Platte River Basin	Moderate to large	Unconsolidated deposits	Poor – Hydrologically connected
	Non-alluvial	Throughout Platte River Basin	Moderate to large	Primarily unconsolidated terrace deposits	Poor – Likely to be hydrologically connected
Tertiary	Late	Within and along margins of structural basins	Moderate to large	Ogallala, Arikaree, White River, Moonstone, Split Rock, Browns Park	Poor– Groundwater control areas in eastern basin. Very good in Split Rock formation.
Tertiary	Early	Within and along margins of structural basins	Small to large	Wasatch and Fort Union and equivalents	Fair
Mesozoic	Late Cretaceous	Structural basins	Small to large	Ferris, Lance, Fox Hills, Medicine Bow, Mesaverde, Frontier	Fair to good
Mesozoic	Early Cretaceous	Structural basins - limited surface exposures	Small to moderate	Muddy Sandstone, Cloverly, Inyan Kara	Fair – insufficient yields and marginal water quality.
Mesozoic	Triassic Jurassic	Structural basins - limited surface exposures	Small to moderate	Nugget Sandstone Sundance	Fair – insufficient yields and marginal water quality.
	Late	Exposed on flanks of uplifts	Small to large	Casper, Madison, Amsden, Hartville, Tensleep,	Very good – target aquifers for nine of the top ten prospects.
	Early	Largely absent in Platte River Basin		Englewood, Fremont Canyon, Bighorn, Buck Spring, Flathead Sandstone	Poor - largely absent.
Precambrian	Precambrian	Structural uplifts	Small to moderate	Undifferentiated	Poor – insufficient yields

by the specified beneficial use(s) and technical limitations. Two of the potentially most productive regional hydrogeologic units in the Platte River Basin are the Quaternary alluvial and Late Paleozoic aquifers. Unfortunately, while Quaternary alluvial aquifers may have local development potential from a hydrogeologic perspective, any new development may be limited by the provisions of the Modified North Platte River Decree and the PRRIP because these aquifers are considered to be hydrologically connected to Platte River surface flows (**Figure 9-1**). Additionally, although well yields could be expected to range from 10 to 500 gpm in these aquifers, water quality and susceptibility to surface sources of contamination (e.g. irrigation return flows and spills from energy development activities) should be considered in evaluating development prospects.

The early Paleozoic aquifers, primarily the Madison Limestone and the Tensleep and Casper sandstones have great potential for developing high-yield wells, depending on site-specific hydrogeologic conditions (Trihydro Corporation, 2007b). Expected yields of 1,000 to 2,000 gpm per well and maximum total well depths of 1000 feet below ground surface (bgs) were projected for the nine Late Paleozoic prospects listed among the top 10 prospects. Because well yields in Paleozoic aquifers are highly dependent on secondary permeability, actual production rates could vary from 10 – 5,000 gpm. The large variations in structure- and solution-controlled permeability require that site-specific investigations must be conducted to evaluate new development prospects.

Interestingly, the best site identified for groundwater augmentation development in the NPRGAS report was the Late Tertiary Split Rock Prospect located 20 miles southeast of Muddy Gap Junction, Wyoming. It was expected that wells completed in the targeted White River, Arikaree and Ogallala formations would reach total depths of 2,700 feet bgs and sustain an estimated annual pumping rate of 3,300 gpm.

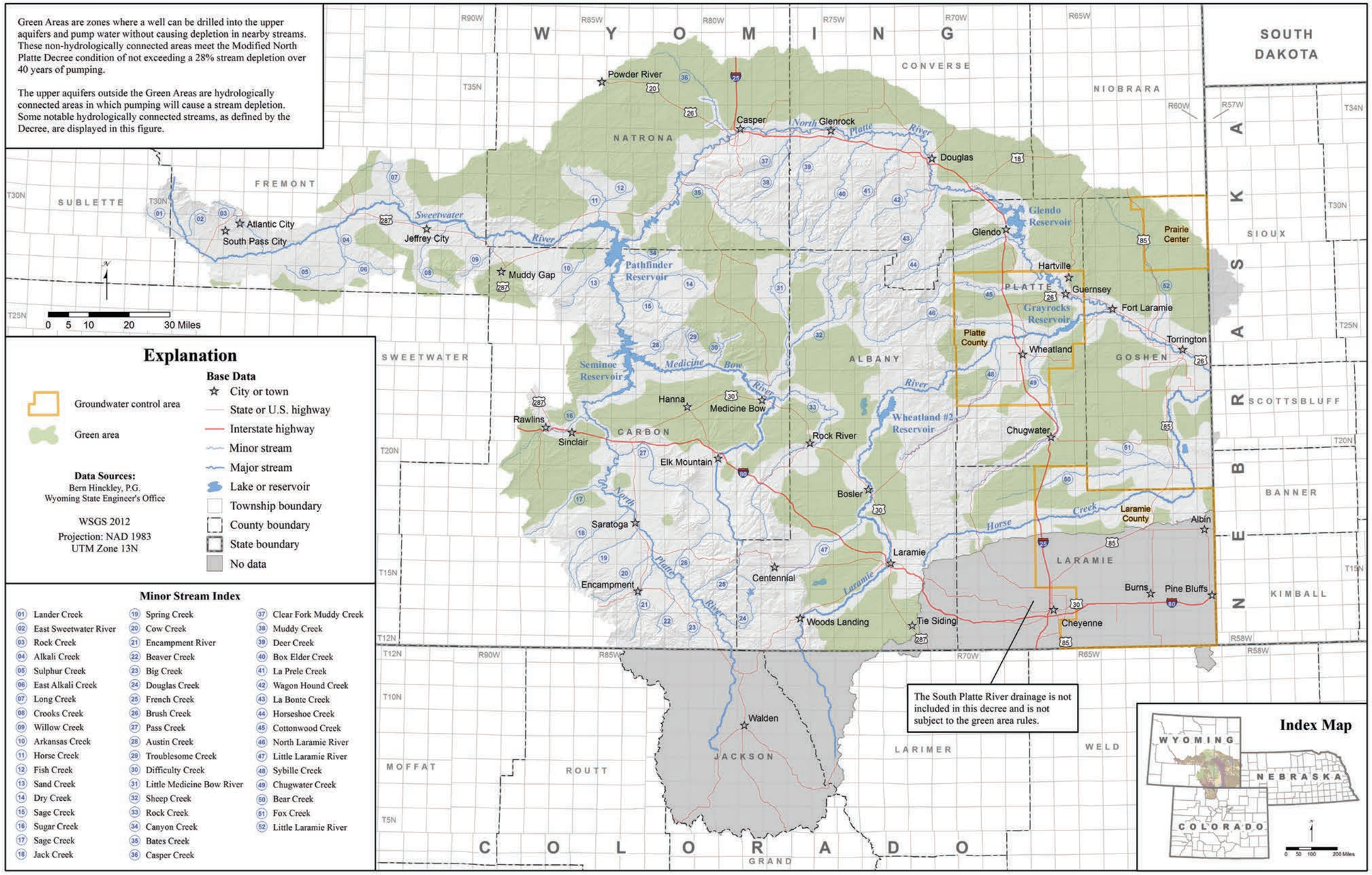


Figure 9-1. Areas that are not "hydrologically connected" and Groundwater Control Areas.

9.1.4 Recent WWDC groundwater development prospects

An examination of recent WWDC groundwater development projects provides, perhaps, the most realistic evaluation of future groundwater development in the Platte River Basin. The recent projects are driven by present and expected future needs of municipalities that are likely to experience population adjustments in the coming years as the economy of Wyoming becomes increasingly centered on energy production and continues to focus on the economic development of groundwater resources relative to the issues discussed in **Section 9.1.** Recent groundwater projects from the WRDS Water Library are presented to illustrate viable future prospects, some of which have been identified for several years, for new and additional public-support groundwater development in the Platte River Basin:

9.1.4.1 Cheyenne

The City of Cheyenne conducted a multi-phase investigation (Lytle Water Solutions, LLC, 2011) of the feasibility and benefits of aquifer storage and recovery (ASR) technologies and recharge infiltration basin (RIB) technologies on four separate well fields located west of the city. The wells in these fields, completed primarily in the Ogallala aquifer, are experiencing water level declines and associated production losses. Pilot-level tests indicated that well levels in the Happy Jack and Bell well fields could be augmented by ASR and RIB recharge, most likely during years of sufficient excess surface flows in Middle Crow Creek.

Groundwater studies have been completed on the City of Cheyenne's Belvoir Ranch in both the Tertiary High Plains (Trihydro Corporation, 2009) and Paleozoic Casper aquifers (Lidstone and Associates, 2012). The data collected during the survey suggests that although the White River Formation in this vicinity produces good quality water, it will not yield sufficient quantities of groundwater for use as a regular municipal supply. At some locations, however, the White River may produce enough water to serve as a minor alternative supply. Data collected from four test wells completed in the Casper aquifer suggested that future development is promising but requires collecting additional geological and hydrogeological data using a phased approach to understand how this resource can be sustainably developed.

Currently, the USGS is also investigating the geologic and hydrogeologic characteristics of the Ogallala Formation and White River Group on the Belvoir Ranch (Bartos and others, 2013).

9.1.4.2 Douglas

Recent groundwater development studies (DOWL HKM, 2010; Weston Engineering, Inc., 2008) for the City of Douglas have focused solely on the Paleozoic aquifer that outcrops to the west and south of the city. Currently, Douglas obtains groundwater supplies from two Paleozoic aquifer facilities, Box Elder Springs and the Sheep Mountain Well. Although, the DOWL HKM (2010) study briefly examined hydrogeologic units ranging from the Ogallala Formation through the Fremont Canyon Sandstone, the Paleozoic aquifer was recognized as the only target formation in the vicinity of Douglas that can provide sufficient quantities of water for a municipal supply. The DOWL HKM (2010) study evaluated seven Paleozoic aquifer groundwater prospects as potential sites for a future high volume production municipal well.

9.1.4.3 Elk Mountain

An additional water supply well was completed and tested in the Cretaceous Cloverly Formation for the Town of Elk Mountain Groundwater Development Program (PMPC, 2011). The new well, Elk Mountain Well No. 4, is a deep (~2,900 ft bgs), that falls within a mutual zone of interference with a nearly identical well, Elk Mountain Well No. 3, located approximately 900 feet to the northeast. Both wells can produce 75 – 100 gpm over several hours of continuous pumping; these production levels are sufficient for the needs of the Town of Elk Mountain. Water quality is excellent with the exception of elevated levels of hydrogen sulfide, which can be easily treated with chlorination. Due to their depth and the confined nature of the Cloverly Formation, the well was determined not to meet the criteria for hydrologic connection in the PRRIP.

9.1.4.4 Encampment

A Level II study examined the feasibility of augmenting Encampment's water supply by connecting to the Sierra Madre Well completed in the Tertiary North Park Formation and owned by the neighboring Town of Riverside. Water production rates are in excess of the current needs, quality is within EPA standards and there is no evidence for long-term decline in aquifer water levels.

9.1.4.5 Glendo

A test well was installed and completed in the Paleozoic Hartville aquifer one mile north of Glendo. The well, Thomas Memorial Well No. 1 is capable of producing 200 gpm and water quality is suitable for a potential municipal supply well (Wyoming Groundwater, LLC, 2009). It is recommended that the Town of Glendo purchase the Thomas Memorial Well No. 1 from WWDC, install a pressure transducer in the well to define water level fluctuations and design and construct the necessary water delivery infrastructure to integrate the well into the town's public water system.

9.1.4.6 Glenrock

In order to provide the Town of Glenrock with a redundant water supply, Glenrock Test Well No. 7 (Weston Engineering, Inc., 2007) was completed in the Paleozoic aquifer to a total depth of 1,233 feet bgs. The well can provide up to 1500 gpm of good quality water. It is recommended that the Town of Glenrock purchase the Glenrock Test Well No. 7 from WWDC and design and construct the water delivery infrastructure required to integrate the well into the town's public water system.

9.1.4.7 Lance Creek

Level I (WWC Engineering, 2011) and Level II (Wyoming Groundwater LLC, in press) Water Supply Studies were conducted for the Town of Lance Creek that examined the public water system and current groundwater wells to find a new source of water for the town. Test Well State No. 2 completed at a total depth of 303 bgs in the Cretaceous Inyan Kara group can produce approximately 55 gpm of water suitable for a public water system.

9.1.4.8 Laramie County

The Laramie County Aquifer Study (JR Engineering, 2009) examined the hydrogeologic status of the High Plains aquifer system. A "Water Resource Atlas of Laramie County, Wyoming" was prepared as a result of this study.

The USGS is currently conducting a hydrogeologic evaluation of the High Plains and the Lance/Fox Hills aquifer systems south of Pine Bluffs, Wyoming (T. Bartos, oral commun.). USGS water scientists are seeking to characterize the hydrogeologic properties and hydrodynamics of both systems as well as explore system development potentials and determine the degree of hydrologic communication between the two aquifers. Preliminary results suggest that sandstone strata in the Fox Hills aquifer may be productive. A report is expected in the next two years.

9.1.4.9 Laramie

The City of Laramie conducted an investigation (Jehn Water Consultants, Inc., 2010) of the feasibility and benefits of aquifer storage and recovery (ASR) technologies in the Spur well field located north of the city. The wells in this field, completed in the Paleozoic Casper aquifer, have experienced water level declines averaging about 1 foot/year since the beginning of the last decade. Pilot-level tests indicated that well levels in the Spur well field could be augmented with ASR recharge by pumping excess water from other city well fields and the Laramie River through Laramie's existing distribution system. It was recommended that further testing and analysis be completed.

9.1.4.10 Manville

Level I (Olsson Associates, 2008) and Level II (Wyoming Groundwater LLC, in progress) Water Supply Studies are being conducted in Manville. Several pilot holes have been drilled into the Paleozoic aquifer to evaluate the feasibility of completing a new municipal supply well for the town.

9.1.4.11 Split Rock aquifer

Trihydro Corporation (2008b) evaluated the feasibility of developing the Split Rock groundwater prospect for replacement water to offset depletions as stipulated in the Modified North Platte River Decree. The Tertiary Split Rock aquifer at the location of this well does not meet the Decree criteria for being hydrologically connected to flows in the North Platte River. Three monitoring wells and two test borings were completed to evaluate the hydrodynamics of the Split Rock and adjacent overlying aquifers, and to characterize the hydrogeology of the Split Rock prospect. A 10 day step rate discharge test, a 30 day constant rate discharge test (1,400 gpm) and water quality testing were conducted on one test production well (SR-1), completed in the Split Rock aquifer at a depth of 2,460 feet bgs. The testing indicated that the Split Rock aquifer is confined, can sustainably produce quantities of water that are sufficient for replacement supply to the North Platte River and is not in hydrologic communication with overlying aquifers or local surface water discharges. Analyses showed that water quality was adequate for use as augmentation water.

9.1.4.12 Riverside

A new municipal water supply well (Riverside No. 7) was completed in deeper zones of the Tertiary North Park aquifer (PMPC, 2011) and tested. Data indicate that Riverside No. 7 could produce a maximum of 400 gpm and water quality was excellent. It was undetermined if the new well meets the criteria for hydrologic connection in the PRRIP.

9.1.4.13 Yoder

A test well was installed and completed in the Cretaceous Fox Hills formation approximately 150 feet northwest of the town's existing water department control building. The well, Yoder Test Well No. 1 is capable of producing 90 gpm and water quality is suitable for a potential municipal supply well (Wyoming Groundwater, LLC, 2011). It is recommended that the Town of Yoder purchase the Yoder Test Well No. 1 from WWDC, and design and construct the necessary water delivery infrastructure to integrate the well into the town's public water system.

The Modified North Platte River Decree and the PRRIP have largely restricted new water use opportunities to the development of groundwater resources in areas that are not hydrologically connected to surface flows in the North Platte River. As can be seen from the brief reviews of recent WWDC funded water projects, the target aquifers for new groundwater development consist primarily of Paleozoic, Tertiary and Cretaceous units. These aquifers are located within green areas, will require site specific investigations to demonstrate lack of hydrological connection or may necessitate the purchase and abandonment of replacement water rights.

WWDC is also encouraging Wyoming municipalities to consider the formation of regional water supply systems. Some of the potential advantages of regionalization include reduced water costs to small consumers, ensured continuity of service should one source water facility go down, redundant reliable municipal water supplies and connecting water delivery infrastructure. An example of such a system in the Platte River Basin can be found in the *Natrona County Regional Water Supply Project Level II Feasibility Study, Final Report,* (Civil Engineering Professionals, Inc., 1994).

9.1.5 Current WWDC groundwater development prospects

By Keith E. Clarey, P.G., Project Manager, Wyoming Water Development Office (WWDO)

As of November 2012, the Wyoming Water Development Commission (WWDC) has several projects in progress within the Platte River Basin of Wyoming. These projects include:

- A new Arikaree Formation water supply well was constructed for the Town of Burns (Laramie County) and located to the northwest of the Town.
- An irrigation well was constructed in Quaternary terrace gravel deposits in the northwestern part of the City of Torrington (Goshen County) to replace an older irrigation well that had a pump stuck in the well and well casing problems.

Some WWDC projects that may occur in the near future in the Platte River Basin include:

- A construction project for the City of Douglas (Converse County) that will make improvements to the spring box used for their municipal water supply.
- A possible test well to be constructed into the Fox Hills Sandstone for the community of Hawk Springs (Goshen County).
- A replacement water supply well offsetting an existing water supply well for the Town of Guernsey (Platte County).
- A possible test well for the community of Jeffrey City (Fremont County).

In addition to the WWDC projects in the Platte River Basin, the U.S. Geological Survey (USGS) commenced in November 2012 the drilling a series of approximately three (3) nested test wells located to the south of the Town of Pine Bluffs (Laramie County). At least one of these USGS wells is planned to fully penetrate the High Plains Aquifer (Ogallala Formation, Arikaree Formation, and White River Group) and continue penetration through the Lance Formation, Fox Hills Sandstone, and stop drilling in the top of the Pierre Shale. The USGS will lithologically and geophysically log these wells and collect core samples through these formations. Information collected from these test wells will be available from the USGS Wyoming Water Science Center located in Cheyenne, Wyoming.

9.1.6 Current SEO project in the Laramie county groundwater control area

By Lisa Lindemann, P.G., Administrator Groundwater Division, Wyoming State Engineer's Office (SEO)

The High Plains aquifer system underlying most of Laramie County has probably been over appropriated since the 1970's. As a result, the Laramie County Control Area was established by the Board of Control on September 2, 1981. The Laramie County Control Area (Control Area) comprises much of the county, but generally includes the High Plains aquifer system and Upper Cretaceous aquifers from about Interstate I-25 eastward to the Wyoming-Nebraska state line.

The Board of Control may designate a control area for the following reasons:

- The use of underground water is approaching a use equal to the current recharge rate;
- Ground water levels are declining or have declined excessively;
- Conflicts between users are occurring or are foreseeable;
- The waste of water is occurring or may occur; or
- Other conditions exist or may arise that require regulation for the protection of the public interest. (W.S. §41-3-912).

When an application to appropriate groundwater for any use other than domestic or stockwatering purposes, or upon filing a petition to amend an existing water right in the Control Area, notice of the application or petition is published in the local paper once a week for three consecutive weeks. Subsequent to the public notice, there is a 10-day period during which protests can be filed on the grounds that there is no *unappropriated* water in the proposed source of supply or that the granting of the application would be detrimental to the public interest. If objections are filed within the time specified, the State Engineer shall set a date for a hearing on the application or requested changes and the objections to such and shall notify the applicant or petitioner and the objectors. If the applicant or petitioner questions the standing of the objector, the state engineer shall make written findings of fact on the issue and may overrule the objection on that basis. The hearing shall be before the control area advisory board and the state engineer or state board of control, and shall be held in an appropriate place within the county in which the proposed well or requested change is to be located. (W.S. §41-3-932(a)).

If no objections are filed against the application or petition but the State Engineer is of the opinion that the application or petition may be detrimental to the public interest, or desires to obtain the recommendations of the Control Area Advisory Board, he shall set a date for a hearing on the application or petition and shall notify the applicant or petitioner of the time and place thereof. The hearing shall be open to the public,

and shall be held before the Control Area Advisory Board and the State Engineer or the State Board of Control in an appropriate place in the county in which the proposed well or requested change is to be located. In making any determination required by this section, the State Engineer may rely upon records and information on file in his office or in the office of the board. In the event a hearing is held he shall make known to the parties the records and information upon which he relies. The state engineer, for good cause, may impose costs of the hearing proportionally upon the applicant or petitioner and the objectors (W.S. §41-3-932(b)).

The application or petition shall be granted and the permit issued only if the State Engineer finds, after receiving the advice of the Control Area Advisory Board, that there are *unappropriated* waters in the proposed source, that the proposed means of diversion or construction is adequate, that the location of the proposed well or other work does not conflict with any well spacing or well distribution regulation, and that the proposed use would not be detrimental to the public interest. If the State Engineer finds that the application or petition is incomplete or otherwise defective, he shall return the application or petition for correction. If the correction is not made within ninety (90) days, the application or petition shall be rejected. (W.S. §41-3-932(c)).

9.1.6.1 State Engineer's Temporary Order

Responding to mounting concerns over increasing development and use of groundwater resources in southeast Wyoming, the State Engineer issued a *Temporary Order Adopting Well Spacing Requirements within the Laramie County Control Area* on April 11, 2012. The Order temporarily limits groundwater development in the Laramie County Control Area until October 1, 2013. The order establishes well spacing restrictions (horizontally and vertically), as well as use limitations for most new groundwater applications and changes to existing water rights in the Control Area.

Subsequent to October 1, 2013, the State Engineer may wish to adopt more permanent corrective controls in the Control Area. However, between now and October 1, 2013, the State Engineer is mandated by statute to perform several activities before he can proceed with either adopting corrective controls of a more permanent nature or with rulemaking to authorize mandatory corrective controls.

The first activity is to determine if there is *appropriable* water available in the Control Area. Subsequently, the State Engineer can proceed with several other actions authorized by statute, including:

- Determining the area and boundaries of districts overlying the various aquifers yielding underground waters in this state and to assign to each district a distinctive name or number *(W.S.§ 41-3-910).*
- Establishing subdistricts when parts of an aquifer require or may require separate regulations from the rest *(W.S.§ 41-3-910).*
- Altering the boundaries of such districts and subdistricts at any time *(W.S.§ 41-3-910).*
- Establishing different districts for different aquifers that overlie each other in whole or in part *(W.S.§ 41-3-910).*
- Causing a hearing before the Control Area advisory board to determine whether the underground water in the area is adequate for the needs of all appropriators of underground water in such area. *§41-3-915(a)*
- Adopting one or more of the following corrective controls:
    - Close the controlled area to any further appropriation of underground water;
    - Determine the permissible total withdrawal of underground water in the control area for each day, month or year, and, insofar as may be reasonably done, apportion such permissible total withdrawal among the appropriators holding valid rights to the underground water in the control area in accordance with the relative dates of priority of such rights;
    - Order such junior appropriators to cease or reduce withdrawals if withdrawals by junior appropriators have a material and adverse effect upon the supply available for and

needed by senior appropriators;
  - Require and specify a system of rotation of use of underground water in the controlled area if cessation or reduction of withdrawals by junior appropriators will not result in proportionate benefits to senior appropriators,
  - Institute well spacing requirements if permits are granted to develop new wells *(W.S. §41-3-915(a)(i – iv).*
- Making regulations concerning the spacing, distribution and location of wells in critical areas (i.e., control areas) *(W.S. §41-3-909(v).*
- Recommending the redesignation of the geographic or stratigraphic boundaries of a control area *(W.S. §41-3-912 (d)).*
- Whenever a control area has been designated or redesignated, refusing to grant permits for the drilling of any wells within the control area without hearings or other proceedings *(W.S. §41-3-912 (g)).*

In addition to corrective controls, appropriators of underground water from a control area may voluntarily agree to any method or scheme of control of withdrawals, well spacing, apportionment, rotation or proration of the common supply of underground water. The State Engineer shall encourage and promote such agreements and supply the parties with information and advice (W.S. §41-3-915(c)).

NOTE: The press release regarding the State Engineer's Temporary Order is available on the SEO's website under "News & Press Releases", as well as the State Engineer's Temporary Order.

9.1.6.2 Hydrogeologic Study of the Laramie County Control Area

The State Engineer's Office recently contracted with AMEC Environment & Infrastructure, Hinckley Consulting, and HDR, Inc. to conduct a hydrogeologic study of the Laramie County Control Area. The purpose of the study is to inform future management decisions regarding the groundwater resource in the area.

The purpose of this hydrogeologic study is to use existing geologic, hydrogeologic, and water rights information within the Control Area to model the groundwater resources. Results will be used to confirm or redescribe the boundaries of the Control Area and Districts within the Control Area. Using those results, the study will provide recommended methods for corrective controls within each of the districts or areas. Resulting information will be used by the State Engineer to evaluate and determine if there is appropriable water in the Control Area.

The proposed project comprises four primary objectives:

- Compile existing geologic and hydrogeologic information and develop parameters to use in modeling the groundwater resources in the Laramie County Control Area (i.e., the High Plains aquifer system, including the Ogallala, White River and Arikaree Formations).
- Evaluate the water rights information and patterns of use to use for modeling the groundwater resources in the Laramie County Control Area.
- Re-evaluate (using the information determined under objectives 1 and 2) the boundaries of both the Control Area and the five districts within the Control Area overlying the High Plains aquifer system. This objective may involve re-describing the control area and / or district boundaries.
- Develop and evaluate potential corrective control measures designed to arrest, or reverse, downward trending water levels and recommendation relative to developing regulations concerning the spacing, distribution and location of wells in the Control Area. This objective should attempt to correlate the potential control measures to different districts identified under objective 3.

9.1.7 Groundwater interference and interconnection with surface water

Other factors that must be considered for new groundwater projects in-development are the potential for interference between wells or well fields completed in the same aquifer, excessive drawdowns in over-utilized aquifers, and interconnections between

groundwater and surface water. These issues have been encountered and in some cases, addressed in the Platte River Basin. The recent WWDC groundwater development projects in Elk Mountain (PMPC, 2011a) and Riverside (PMPC, 2011b), reviewed in the previous section, reported cases of well interference between a newly installed test well and previously completed municipal wells. Well interference, alone, does not necessarily present significant problems to a public water system depending on several factors including but not limited to, the physical and hydrogeologic properties of the target aquifer, construction of the production wells and the timing and rate(s) of well production. In aquifers that possess high degrees of secondary (fracture) permeability, well interference may be unavoidable over the scale of several miles. In many cases, municipal water supply personnel, who are aware of well interference effects in their facilities, effectively manage them by adjusting well pumping times and rates, or periodically switching to other sources of municipal water.

Excessive drawdown, or groundwater depletion, in over-utilized aquifers has become a national concern (Konikow, 2013). In the Platte River Basin, particular attention is given to the issue of groundwater depletion in the High Plains aquifer system (JR Engineering, 2008; 2009b; Bartos, and Hallberg, 2011; Bartos and others, 2013). The SEO has contracted with AMEC Environment & Infrastructure, Hinckley Consulting, and HDR, Inc. to conduct a hydrogeologic study of the Laramie County Control Area in response to regulatory issues and concerns about the status of the High Plains aquifer in southeast Wyoming. The study will be used to inform groundwater management decisions by the SEO and other regulatory agencies.

Although the nature and extent of interconnections between groundwater and surface water have been broadly investigated in the Platte River Basin with respect to the specific "hydrological connection" criteria of the Modifed North Platte Decree, this important issue remains to be evaluated on a case-by-case basis for many situations.

9.2 Recommendations for future updates

The quality of the Wyoming State River Basin water plans and Water Plan updates is limited by the availability of data and the institutional resources used to develop the compiled information in a form that is readily accessible and useful to stakeholders in groundwater development. While some information (e.g., hydrogeology studies, SEO groundwater permit, data from the DEQ and other agencies) is generally available for all basins, other information (e.g. regional groundwater modeling) does not exist. The quantity, accuracy, and completeness of available groundwater information vary between and within the major drainage basins of Wyoming.

The purpose(s) of updating an Available Groundwater Determination can be to include new information generated since the previous determination, to include older information not initially provided, and to utilize continuously improving technology to maximize the value of the relevant information that is presented. While information in some areas will grow slowly (e.g., mapping of geologic and hydrogeologic units), other information (e.g., WSEO and other agency data) requires regular updates to maintain its utility.

9.2.1 Data challenges

Computing capabilities will continually improve but will always be limited by the availability and reliability of the input data. The quality of a compilation study, such as this, relies on the quality of the available data. The development of a comprehensive statewide database for water quality and aquifer physical characteristics would greatly assist Wyoming water professionals to manage and protect the state's valuable water resources.

Currently, hydrogeologic and hydrogeochemical data exist that could be integrated into a more comprehensive and evolving groundwater database for Wyoming. For example, DEQ collects copious amounts of groundwater data for site-specific investigations of contaminated sites, for issuing industrial permits (e.g. mining, Underground Injection Control, waste and wastewater management), and for monitoring for potential impacts, and other activities. The SEO collects groundwater information from selected wells. The USGS, WOGCC, BLM, EPA, counties,

municipalities, other agencies, and private entities all collect hydrologic information for a variety of activities and purposes. However, coordination between the various entities collecting groundwater information is generally lacking; and clearly there is abundant relevant information that was not and is not accessible for this study and groundwater determinations in other basins. While the quality of some of this information may not be consistent with the standards described in **Chapter 7**, those data could be qualified. Although, some data (e.g., on contaminated samples) would not be representative of natural groundwater, and some water quality analyses (e.g., for contaminated sites and industrial site monitoring) will be for constituents not commonly used to characterize natural groundwater quality; nevertheless, a comprehensive database would be useful.

Ongoing revision and maintenance of a comprehensive groundwater information database where data are continually being generated by numerous entities would be a substantial project, requiring a continuing commitment of resources by Federal, State, and local agencies and is certainly easier described than done. As interest in groundwater resources increases, so will justification for such a program.

9.2.2 Current and future research efforts

This study is a compilation of previous investigations conducted primarily by state and federal agencies and consultants. Any significant advancement in the development of the conceptual model of the hydrogeology of the Platte River Basin or its Laramide sub-basins will require further original research, most likely conducted by academic investigators, USGS water scientists, or by consultants employed by the WWDC, SEO or Wyoming municipalities. Three particular research efforts currently being conducted should prove to be particularly valuable to a better understanding of groundwater resources in the Platte River Basin:

- **Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG)** - The development of **WyCEHG** at the University of Wyoming will likely result in original hydrologic research in the Platte River Basin and other drainage basins in the state. Funded for a five year period by the National Science Foundation, WyCEHG efforts are specifically targeted to advancing research in western hydrologic systems using advanced geophysics and remote sensing technologies. The stated goals of WyCEHG are:
  - **To improve understanding of mountain front hydrology** by characterizing the processes that partition water into streams, soils, plants, rivers and aquifers in several locations throughout the state.
  - **To improve understanding of how disturbances affect water flux** by studying effects on hydrological systems from climate change, bark beetle infestations, and energy extraction.
  - **To improve integrated modeling of the fate and transport of water** by creating integrated computer models that will provide the scientific knowledge and tools for improved prediction of hydrological processes.
  - **To provide cutting edge resources and tools** for educators and watershed managers in the state.

  Further information can be obtained from the website for WyCEHG which can be accessed at: http://www.uwyo.edu/epscor/wycehg/.

- **USGS Lance/Fox Hills Study** - Building on three earlier U.S. Geological Survey (USGS) studies of the High Plains aquifer system in Laramie County (Hallberg and Mason, 2007; Bartos and Hallberg, 2011; Bartos and others, in preparation), the USGS study proposes additional characterization of the High Plains aquifer system in eastern Laramie County, as well as characterization of underlying Upper Cretaceous aquifers (Lance Formation and Fox Hills Sandstone) which likely have some potential to be utilized as a supplemental or alternative water supply to the High Plains aquifer system.

  The objectives of the study are to:

  - Improve understanding of the physical and chemical characteristics of the Tertiary

High Plains aquifer system (primarily White River Group) and underlying Upper Cretaceous aquifers (Lance Formation and Fox Hills Sandstone) in eastern Laramie County, Wyoming, and initially evaluate the relative hydraulic connection between the aquifer system and aquifers; and

- Improve understanding of recharge to and apparent groundwater age of the High Plains aquifer system and Upper Cretaceous aquifers at the location selected for objective 1 through the use of chemical tracers in the unsaturated and saturated zones.

A USGS Scientific Investigations Report (SIR) will be prepared describing the results of the study. The report will consist of text, tables, illustrations, and photographs of core and/or thin sections, as well as one or two plates—the plates will graphically show/describe the physical, chemical, and geophysical characteristics of the entire exploratory borehole at the drilling site. The results of this study will be placed in the context of all previous investigations in order to improve understanding of these critically important aquifers in southeast Wyoming and in the United States.

Also, the USGS is currently (2013) constructing a new groundwater-flow model of the northern High Plains aquifer system, including Wyoming (U.S. Geological Survey, 2013). The new model builds upon and refines work conducted previously as part of the USGS RASA High Plains aquifer system study. The model is being constructed using MODFLOW "as a tool to understand how the aquifer responds to the continuing and in some cases growing demands on the groundwater resources in the northern High Plains aquifer" (U.S. Geological Survey, 2013). Additionally, a water budget will be developed for the entire aquifer system.

The recharge calculations based on the surface outcrop area of hydrogeologic units and the SDVC map of recharge (Hamerlinck and Arneson, 1998), contained in Section 6.2 of this study, went beyond summarizing existing information by using the data to estimate the groundwater resource. The recharge evaluation in this study could easily be updated and the results refined as new data is collected, with a relatively low-level commitment of resources. The estimation of recharge can be enhanced by updated numerical modeling that includes additional variables that affect infiltration and recharge (**Section 5.1.3**). There are several other areas where useful information could be developed for future Platte River Basin Water Plan updates:

- More detailed geologic mapping to better define the function of hydrogeologic units as aquifers or confining units based on lithology, stratigraphic position, and structural relationships.
- Priority ranking of areas where numerical modeling would be most useful.
- Identification of additional areas where interference between wells and well fields should be considered in evaluating future groundwater development.
- Updated identification of areas where groundwater and surface water may be interconnected.
- Inclusion on the surface hydrogeology map (**Plate II**) of shallow anticlinal axes that may affect groundwater flow.
- Mapping linear segments of surface-water drainages, primarily where tertiary geologic units are exposed or thinly covered by quaternary deposits in the basin interiors, to identify areas where vertical recharge may be enhanced by fracture permeability.
- Mapping irrigation drain systems and sampling the discharge points to provide spatially-averaged water quality of the shallowest groundwater in local irrigated areas.
- Mapping areas covered by WWDC studies listed in **Appendix B.**
- Developing a website where stakeholders can submit information and comments relevant to future available groundwater determinations.
- Developing additional and specific information on institutional, legal, and cultural issues that could affect groundwater development in the Platte River Basin

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Appendix A

Description of Geologic Units

Richard Hays, Brett Worman, and Scott Quillinan

APPENDIX A: Description of GIS Geologic Units, Platte River Basin

This appendix describes the 115 digital Geographic Information System (GIS) geologic units that comprise the Platte River Basin of Wyoming, Colorado, and Nebraska. The stratigraphic descriptions in this appendix are for the units shown on **Plate I**. The 115 digital GIS geologic units are distributed as follows:

Wyoming	*82 geologic units*	*page A1-11*
Colorado	*27 geologic units*	*page A11-13*
Nebraska	*6 geologic units*	*page A1-11*

These geologic units are compiled from the 1:500,000-scale digital state maps that cover the Platte River Basin. The maps give a code and rock-type description to each unit within the mapped state; each state has its own set of codes, and neither codes nor unit boundaries necessarily match across state lines.

In this appendix, for each state, each geologic unit symbol (**bold face**) and GIS definition (underlined) is followed by a description of the corresponding stratigraphic unit(s) as defined in that state. **Plate 1** summarizes these determinations. The abbreviation "Ma" in the following descriptions denotes "million years before present." Rock-stratigraphic units that appear in the right-hand column of **Plate 1 and 2** are in **boldface**.

PLATTE RIVER BASIN GEOLOGIC UNITS – WYOMING & NEBRASKA

There are 82 digital GIS geologic units in the Wyoming portion of the Platte River Basin and 6 digital GIS geologic units in the Nebraska portion (Love and Christiansen, 1985; Stoeser et al., 2005). The stratigraphic descriptions below are taken directly from Love and Christiansen (1985) with minor modifications.

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Symbol ***Unit Description***

CENOZOIC GEOLOGIC UNITS – WYOMING

Quaternary geologic units – Wyoming & Nebraska

Qa Alluvium and colluvium (Holocene-Pleistocene) – Clay, silt, sand, and gravel in flood plains, fans, terraces, and slopes.

Qt Gravel, pediment, and fan deposits (Holocene-Pleistocene) – Mostly locally derived clasts; locally includes some Tertiary gravels.

Qg Glacial deposits (Holocene-Pleistocene) – Till and outwash of sand, gravel, and boulders.

Symbol	*Unit Description*
Qls	Landslide deposits (Holocene-Pleistocene) – Local intermixed landslide and glacial deposits, talus, and rock-glacier deposits.
Qs	Dune sand and loess (Holocene-Pleistocene) (present in Nebr.) – Active and dormant sand dunes.
Ql	Playa lake and other lacustrine deposits (Holocene-Pleistocene) – Chiefly clay, silt, and fine sand. Includes travertine deposits.
Qu	Undivided surficial deposits (Holocene-Pleistocene) – Mostly alluvium, colluvium, and glacial and landslide deposits.
QTg	Terrace gravel (Pleistocene and (or) Pliocene) – Partly consolidated gravel above and flanking some major streams.
QTc	Conglomerate (Pleistocene to Miocene) – Giant granite boulders in arkose matrix.
QTb	Bug Formation (Pleistocene or Pliocene) – Lacustrine white marl, claystone, sandstone, conglomerate, and tuff; generally radioactive.

Upper Tertiary geologic units – Wyoming & Nebraska

Tm	Miocene rocks (undivided) (Miocene) Miocene rocks – Central Wyoming – White soft tuffaceous sandstone; locally derived conglomerate in upper and lower parts of sequence; some lower conglomeratic sequences may be Oligocene; in Granite Mountains, K/Ar age of tuff in lower part of sandstone sequence ~17 Ma, fission-track age of lower conglomerate ~24 Ma. Miocene rocks – Saratoga Valley and west and southwest to Colorado – White massive soft tuffaceous sandstone and lesser white marl; lower part conglomeratic. Underlies North Park Formation in Saratoga Valley. To the west and southwest is referred to as Browns Park Formation. Miocene rocks – Rawlins Area – White massive soft tuffaceous sandstone.
Tmu	Upper Miocene rocks (undivided) (upper Miocene) upper Miocene rocks – Southeast corner of Wind River Range – Siliceous, arkosic, locally radioactive sandstone, claystone, and conglomerate; fission-track age ~27 Ma. Recent work suggests that part of these deposits may be of Eocene age. Originally defined as the Miocene-Pliocene South Pass Formation. upper Miocene rocks – Saratoga Valley, North Park Formation – White to greenish-gray tuffaceous sandstone, siltstone, and claystone; locally conglomeratic. upper Miocene rocks – Central Wyoming – Arkosic sandstone, conglomerate, and siltstone; some light-colored tuffaceous radioactive claystone and white cherty limestone. upper Miocene rocks – Central Wyoming, Moonstone Formation - North of Sweetwater River in Granite Mountains – Light-colored tuffaceous radioactive claystone, siltstone, sandstone, and arkose. upper Miocene rocks – East Wyoming – Light-colored tuffaceous claystone, sandstone, and conglomerate. Ogallala Formation in Denver Basin.
Tml	Lower Miocene rocks (Lower Miocene) – Central Wyoming – Tuffaceous sandstone, siltstone, and white marl.

Symbol	*Unit Description*
Tmo	Lower Miocene and upper Oligocene rocks (Miocene and upper Oligocene) – Light-colored soft porous sandstone and underlying white tuffaceous claystone and siltstone. Arikaree Formation in Denver Basin.
Tu	Sandstone and Conglomerate (Post Eocene) – Gray, hard, course-grained sandstone and conglomerate.

Lower Tertiary geologic units – Wyoming & Nebraska

Twr	White River Formation (Oligocene; 31-35 Ma) (present in Nebr.) – White to pale-pink, blocky, tuffaceous claystone and lenticular arkosic conglomerate.
Twru	Upper conglomerate member, White River Formation (Oligocene) – Light-gray, soft, conglomeratic, tuffaceous sandstone and conglomerate of Precambrian clasts.
Twrb	Brule Member, White River Formation (Oligocene) – Pale-pink to white blocky tuffaceous claystone and lenticular sandstone. Locally includes the upper conglomerate member.
Twrc	Chadron Member, White River Formation (Oligocene) – Light gray to dark-red, tuffaceous claystone, sandstone, and lenticular conglomerate.
Toe	Oligocene and (or) Upper and Middle Eocene rocks (Oligocene and Eocene) – Light gray tuff, arkosic sandstone, and lenticular conglomerate.
Tid	Dacite and quartz latite intrusive and extrusive igneous rocks (Oligocene and (or) Eocene ~44Ma) – Light gray porphyritic rock.
Tip	Ice Point Conglomerate (Eocene) – Reddish-brown conglomerate, chiefly of Paleozoic rock fragments.
Twb	Wagon Bed Formation (Eocene; ~45-49 Ma) – Central Wyoming – Dull-green, siliceous, bentonitic claystone and tuff; giant granite boulder conglomerate in tuffaceous matrix.
Tb	Bridger Formation (Eocene) – Greenish-gray, olive-drab, and white tuffaceous sandstone and claystone; lenticular marlstone and conglomerate.
Tcg	Crooks Gap Conglomerate (Eocene) – Giant boulders of granite in arkosic sandstone matrix. Reynolds (1976) considers age of eastern exposure to be Oligocene (?).
Tai	Alkalic intrusive and extrusive igneous rocks (Eocene ~44Ma) – Light- to greenish-gray porphyry.
Tgl	Laney Member, Green River Formation (Eocene ~45Ma) – Oil shale and marlstone.
Tgt	Tipton shale Member or Tongue, Green River Formation (Eocene) – Oil shale and marlstone.
Tw	Wasatch Formation (Eocene) – East Wyoming – Drab sandstone and drab to variegated claystone; numerous coal beds in lower part.
Twc	Cathedral Bluffs Tongue, Wasatch Formation (Eocene) – Variegated claystone and lenticular sandstone; conglomeratic near south margin of Wind River Range.

Symbol	*Unit Description*
Twm	Main body, Wasatch Formation (Eocene-Paleocene) – Drab sandstone, drab to variegated claystone, and siltstone; locally derived conglomerate around basin margins. Lower part is Paleocene.
Tbw	Transitional unit between Battle Springs and Wasatch Formations (Eocene) – Interbedded lithologies of Battle Spring and Wasatch Formations.
Tbs	Battle Spring Formation (Eocene-upper Paleocene) – Equivalent to, and lithologically similar to locally derived basin-margin conglomerate of Wasatch Formation; merges southward into main body of Wasatch Formation. Lower part is Paleocene.
Twdr	Wind River Formation (Eocene) – Central Wyoming – Variegated claystone and sandstone; lenticular conglomerate. Age of tuff at top 49 Ma.
Tim	Indian Meadows Formation (Eocene) – Red to variegated claystone, sandstone, and algal-ball limestone; some beds of large Paleozoic boulders and detachment masses of Paleozoic and Mesozoic rocks.
Tco	Coalmont Formation (Eocene and Paleocene) – Tan to gray, arkosic, micaceous, soft sandstone, claystone, and locally derived conglomerate.
Tha	Hanna Formation (Paleocene) – Brown and gray sandstone, shale, conglomerate, and coal; giant quartzite boulders near Medicine Bow Mountains.
Tfu	Fort Union Formation (Northwest, southwest, and central Wyoming) – Brown and gray sandstone, gray to black shale, and thin coal beds.
Tfl	Lebo Member, Fort Union Formation – Dark-gray clay shale and concretionary sandstone.
Tft	Tullock Member, Fort Union Formation – Soft, gray sandstone, gray and brown carbonaceous shale, and thin coal beds.
TKf	Ferris Formation (Paleocene and Upper Cretaceous) – Brown and gray sandstone and shale; sparse carbonaceous shale and coal beds; thin lenses of pebble conglomerate.

MESOZOIC GEOLOGIC UNITS – WYOMING

Upper Cretaceous geologic units – Wyoming

Kl	Lance Formation (Upper Cretaceous) – South and northeast Wyoming – Brown and gray sandstone and shale; thin coal and carbonaceous shale beds.
Klm	Lance Formation and Lewis Shale (Upper Cretaceous) Lance Formation – South and northeast Wyoming – Brown and gray sandstone and shale; thin coal and carbonaceous shale beds. Lewis Shale – Gray marine shale containing abundant interbedded gray and brown lenticular concretion-rich sandstone beds.
Kmb	Medicine Bow Formation (Upper Cretaceous) – Brown and gray sandstone and shale; thin coal and carbonaceous shale beds.

Symbol	*Unit Description*
Kfh	Fox Hills Sandstone (Upper Cretaceous) – Light-colored sandstone and gray sandy shale containing marine fossils.
Kfl	Fox Hills Sandstone and Lewis Shale (Upper Cretaceous) Fox Hills Sandstone – Light-colored sandstone and gray sandy shale containing marine fossils. Lewis Shale – Gray marine shale containing abundant interbedded gray and brown lenticular concretion-rich sandstone beds.
Kml	Meeteetse Formation and Lewis Shale (Upper Cretaceous) Meeteetse Formation (~73 Ma) – Chalky-white to gray sandstone, yellow, green, and dark-gray bentonitic claystone, white tuff, and thin coal beds. Lewis Shale (~68 Ma) – Gray marine shale containing abundant interbedded gray and brown lenticular concretion-rich sandstone beds.
Kle	Lewis Shale (Upper Cretaceous; ~68 Ma) – Gray marine shale containing abundant interbedded gray and brown lenticular concretion-rich sandstone beds.
Kmv	Mesaverde Formation or Group (Upper Cretaceous) – Light-colored, massive to thin-bedded sandstone, gray sandy shale, and coal beds. Rawlins Uplift (South Wyoming) (Upper Cretaceous) Almond Formation – White and brown, soft sandstone, gray sandy shale, coal and carbonaceous shale. Pine Ridge Sandstone – Light gray sandstone and thin coal beds. Allen Ridge Formation – Gray sandstone, shale, and thin coal beds. Haystack Mountains Formation – Gray marine sandstone and shale. Laramie Basin (South Wyoming) (Upper Cretaceous) Pine Ridge Sandstone – Light gray sandstone and thin coal beds. Rock River Formation – Soft sandstone and sandy shale.
Kc	Cody Shale (Upper Cretaceous; 78-83 Ma) – South Wyoming – Dull-gray shale, gray siltstone, and fine-grained gray sandstone.
Kf	Frontier Formation (Upper Cretaceous) – South Wyoming – Gray sandstone and sandy shale.
Kcf	Cody Shale and Frontier Formation (Upper Cretaceous) Cody Shale – South Wyoming – Dull-gray shale, gray siltstone, and fine-grained gray sandstone. Frontier Formation – South Wyoming – Gray sandstone and sandy shale.
Knt	Niobrara and Frontier Formations, and Mowry and Thermopolis Shales (Upper Cretaceous) Niobrara Formation (Upper Cretaceous: ~ 83 Ma) – Light-colored limestone and gray to yellow speckled limy shale. Frontier Formation – South Wyoming – Gray sandstone and sandy shale. Mowry Shale (Upper Cretaceous) – Silvery-gray, hard, and siliceous shale containing abundant fish scales and bentonite beds. Thermopolis Shale (Lower Cretaceous) – Black, soft, and fissile shale with Muddy Sandstone Member at top of unit.
Kft	Frontier Formation and Mowry and Thermopolis Shales (Upper Cretaceous) Frontier Formation – South Wyoming – Gray sandstone and sandy shale.

Symbol	*Unit Description*
Kft (cont.)	
	Mowry Shale (Upper Cretaceous) – Silvery-gray, hard, and siliceous shale containing abundant fish scales and bentonite beds. Thermopolis Shale (Lower Cretaceous) – Black, soft, and fissile shale with Muddy Sandstone Member at top of unit.
Ks	Steele Shale (Upper Cretaceous; ~78 to 82 Ma) – Gray, soft, marine shale containing numerous bentonite beds and thin lenticular sandstone.
Ksn	Steele Shale and Niobrara Formation (Upper Cretaceous) Steele Shale (Upper Cretaceous: ~78 to 82 Ma) – Gray, soft, marine shale containing numerous bentonite beds and thin lenticular sandstone. Niobrara Formation (Upper Cretaceous: ~ 83 Ma) – Light-colored limestone and gray to yellow speckled limy shale.
Kp	Pierre Shale (Upper Cretaceous: ~72-78 Ma) – Dark-gray, concretionary, marine shale; contains several bentonite beds.
Kn	Niobrara Formation (Upper Cretaceous: ~83 Ma) – Light-colored limestone and gray to yellow speckled limy shale.
Lower Cretaceous geologic units – Wyoming	
Kmt	Mowry and Thermopolis Shales (Upper to Lower Cretaceous) Mowry Shale (Upper Cretaceous) – Silvery-gray, hard, siliceous shale containing abundant fish scales and bentonite beds. Thermopolis Shale (Lower Cretaceous) – Black soft fissile shale with Muddy Sandstone Member at top of unit.
Cretaceous and Jurassic geologic units – Wyoming	
KJ	Cloverly and Morrison Formations (Lower Cretaceous to Jurassic) Cloverly Formation – Rusty-color sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base. Morrison Formation – Dully variegated, siliceous claystone, nodular white limestone, and gray silty sandstone.
KJs	Cloverly, Morrison, and Sundance Formations (Lower Cretaceous to Jurassic) Cloverly Formation – Rusty-color sandstone at top, which overlies brightly variegated bentonitic claystone; chert-pebble conglomerate locally at the base. Morrison Formation – Dully variegated, siliceous claystone, nodular white limestone, and gray silty sandstone. Sundance Formation – Greenish-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale.
Jurassic geologic unit – Wyoming	
Js	Sundance Formation (Upper Jurassic to Middle Jurassic) – Greenish-gray, glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale.
Jurassic and Triassic geologic unit – Wyoming	
JTRn	Nugget Sandstone (Jurassic to Triassic (?)) – North Wyoming – Gray to dull-red, crossbedded, quartz-rich sandstone.

Triassic geologic units – Wyoming

Symbol	*Unit Description*
₮c	Chugwater Group or Formation (Upper and Lower Triassic) Chugwater Formation (Upper and Lower Triassic) – Red siltstone and shale. Alcova Limestone Member in upper middle part in north Wyoming. Thin gypsum partings near base in north and northeastern Wyoming. Chugwater Group or Formation (Upper and Lower Triassic) – Red shale and siltstone containing thin gypsum partings near base. Group includes Popo Agie Formation (red shale and red, yellow, and purple siltstone; lenses of lime-pellet conglomerate), Crow Mountain Sandstone (red and gray, thick bedded), Alcova Limestone, and Red Peak Formation (red siltstone and shale). Chugwater Formation includes as members all the units listed above.
₮cd	Chugwater and Dinwoody Formations (Upper and Lower Triassic) Chugwater Formation – Red siltstone and shale. Alcova Limestone Member in upper middle part in north Wyoming. Thin gypsum partings near base in north and northeast Wyoming. Dinwoody Formation – North Wyoming – Olive-drab hard dolomitic thin-bedded siltstone.

MESOZOIC AND PALEOZOIC GEOLOGIC UNITS – WYOMING

MzPz	Mesozoic and Paleozoic rocks (Mesozoic to Paleozoic) – South Wyoming – Mapped in small local areas of complex structure. South side of Granite Mountains north of Green Mountain – Nugget Sandstone, Chugwater and Goose Egg Formations, Tensleep Sandstone, and Amsden Formation (Jurassic (?) through Mississippian) South flank of Ferris Mountains – Nugget Sandstone and Chugwater and Goose Egg Formations (Jurassic (?) through Permian) Northeast flank of Seminoe Mountains – Cloverly, Morrison , Sundance, Chugwater and Goose Egg Formations (Lower Cretaceous through Permian) East flank of Laramie Mountains – Cloverly, Morrison, Sundance, Chugwater, and Goose Egg Formations, and east of fault in T. 19 N., Casper Formation (Lower Cretaceous through Middle Pennsylvanian)

Triassic and Permian geologic units – Wyoming

₮Pcg	Chugwater and Goose Egg Formations (Upper Triassic-Permian) Chugwater Formation (Upper and Lower Triassic) – Red siltstone and shale. Alcova Limestone Member in upper middle part in north Wyoming. Thin gypsum partings near base in north and northeastern Wyoming. Goose Egg Formation – Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone.
₮Pjs	Jelm and Chugwater Formations, Forelle Limestone, and Satanka Shale (Lower Triassic-Permian) Jelm Formation – Red sandstone. Chugwater Formation (Upper and Lower Triassic) – Red siltstone and shale. Alcova Limestone Member in upper middle part in north Wyoming. Thin gypsum partings near base in north and northeastern Wyoming. Forelle Limestone – Thin-bedded limestone. Locally a member of the Goose Egg Formation. Satanka Shale – Red shale.

Symbol	*Unit Description*
ŦPg	Goose Egg Formation (Lower Triassic-Permian) – Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone.

PALEOZOIC GEOLOGIC UNITS – WYOMING

Pzr	Paleozoic Rocks (Permian-Cambrian) – Rattlesnake Hills, east end of Granite Mountains, and north end of Laramie Mountains consists of Madison Limestone and Cambrian rocks.

Permian geologic units – Wyoming

Pp	Phosphoria Formation and related rocks (Permian) – Brown sandstone and dolomite, cherty, phosphatic, and glauconitic dolomite, phosphatic sandstone and dolomite, and greenish-gray to black shale; intertonguing equivalents of parts of Phosphoria are Park City Formation (primarily cherty dolomite, limestone, and phosphatic gray shale) and Shedhorn Sandstone.
Pfs	Forelle Limestone and Satanka Shale (Permian) Forelle Limestone – Thin-bedded limestone. Locally a member of the Goose Egg Formation. Satanka Shale – Red shale.

Permian and Pennsylvanian geologic units – Wyoming

PIPc	Casper Formation (Lower Permian-Upper and Middle Pennsylvanian) – Gray, tan, and red thick-bedded sandstone underlain by interbedded sandstone and pink and gray limestone. May include some Devonian (?) sandstone along east flank of Laramie Mountains.
PIPcf	Casper and Fountain Formations (Lower Permian-Upper and Middle Pennsylvanian) Casper Formation – Gray, tan, and red thick-bedded sandstone underlain by interbedded sandstone and pink and gray limestone. May include some Devonian (?) sandstone along east flank of Laramie Mountains. Fountain Formation – Arkose and red sandstone.
PIPM	Casper Formation and Madison Limestone (lower Permian-Upper Mississippian) Casper Formation – Gray, tan, and red thick-bedded sandstone underlain by interbedded sandstone and pink and gray limestone. May include some Devonian (?) sandstone along east flank of Laramie Mountains. Madison Limestone or Group – Group includes Mission Canyon Limestone (blue-gray, massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty limestone and dolomite).
PIPh	Hartville Formation (Lower Permian-Upper, Middle, and Lower Pennsylvanian) – Red and white sandstone underlain by gray dolomite and limestone, red shale, and red and gray sandstone. Lowermost unit may be Late Mississippian in age.

Permian and Mississippian geologic units – Wyoming

PM	Tensleep Sandstone and Amsden Formation (lower Permian to Upper Mississippian) Tensleep Sandstone (Lower Permian to Upper Mississippian) – South Wyoming – White to gray sandstone containing thin limestone and dolomite beds.

Symbol	*Unit Description*
PM (cont.)	
	Amsden Formation (lower Permian to Middle Pennsylvanian) – South Wyoming – Red and green shale and dolomite with a persistent red to brown sandstone at base.

Mississippian geologic units – Wyoming

Mm	Madison Limestone or Group (Upper to Lower Mississippian) – Group includes Mission Canyon Limestone (blue-gray, massive limestone and dolomite), underlain by Lodgepole Limestone (gray, cherty limestone and dolomite).

Mississippian and Devonian geologic units – Wyoming

MDg	Guernsey Formation (Lower Mississippian and Upper Devonian) – Blue-gray massive cherty limestone and dolomite. Locally includes unnamed dolomite and sandstone of Devonian and Cambrian (?) age.

Ordovician and Cambrian geologic units – Wyoming

O€	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone (Upper Ordovician to Middle Cambrian) Bighorn Dolomite (Upper to Middle Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and locally dolomitic limestone. Gallatin Limestone (Upper Cambrian) – Gray and tan limestone. Gros Ventre Formation (Upper to Middle Cambrian) – Soft, green, micaceous shale (Upper and Middle Cambrian Park Shale Member), underlain by blue-gray and yellow mottled, hard, dense limestone (Middle Cambrian Death Canyon Limestone Member), and soft, green, micaceous shale (Middle Cambrian Wolsey Shale Member). Flathead Sandstone (Middle Cambrian) – Dull-red, quartz-rich sandstone.

Cambrian geologic units – Wyoming

€r	Cambrian rocks (Middle to Upper Cambrian) – Hard, blue-gray and yellow mottled, dense limestone interbedded with soft, green micaceous shale; dull-red quartz-rich sandstone at base.

PRECAMBRIAN GEOLOGIC UNITS – WYOMING

p€r	Precambrian rocks – Middle Proterozoic through middle Archean granitic, metasedimentary, metavolcanic, and mafic intrusive rocks. Sherman Granite (Middle Proterozoic, 1,415-1,435 Ma.) – In Medicine Bow and Laramie Mountains. Laramie Anorthosite Complex (Middle Proterozoic) – In Laramie Mountains – Pyroxene and hornblende syenite – Age 1,435 Ma. Laramie Anorthosite Complex (Middle Proterozoic) – In Laramie Mountains – Anorthosite and norite. Metasedimentary and Metavolcanic rocks (Early Proterozoic) Sierra Madre – Granite gneiss, felsic gneiss, amphibolite, and metavolcanic rocks Medicine Bow Mountains – Granite gneiss, felsic gneiss, hornblende gneiss, and amphibolite. Laramie Mountains – Pelitic Schist, marble, granite gneiss, layered amphibolite, and felsic gneiss.

Symbol	*Unit Description*
p€r (cont.)	

Metasedimentary rocks (Early Proterozoic) – In Medicine Bow Mountains and Sierra Madre – Libby Creek Group – Pelitic schist, amphibole schist, quartzite diamictite, quartz-pebble conglomerate, and marble.

Metasedimentary rocks (Early Proterozoic) – In Medicine Bow Mountains and Sierra Madre – Deep Lake Group – Quartzite, diamictite, pelitic schist, and quartz-pebble conglomerate.

Granitic rocks of 1,700 Ma Age Group (Early Proterozoic) – In Sierra Madre and Medicine Bow Mountains, and Hartville Uplift.

Quartz diorite (Early Proterzoic)

- Sierra Madre – Encampment River Granodiorite (1,800 Ma).
- Medicine Bow Mountains – Keystone Quartz Diorite
- Hartville Uplift – Diorite of Twin Hills.

Mafic intrusive rocks (Early Proterzoic)

- Sierra Madre – Gabbro of Elkhorn Mountain (1,800 Ma).
- Medicine Bow Mountains – Mullen Creek and Lake Owens Mafic Complexes; older than 1,700 Ma.

Granitic rocks of 2,000 Ma Age Group (Early Proterozoic)

- Medicine Bow Mountains – Gaps Intrusion (granitic).
- Hartville uplift – Granite and quartz monzonite of Flattop Butte, age 2,150± Ma.

Mafic Intrusive Rocks (Proterozoic and Late Archean) – In Sierra Madre and Medicine Bow Mountains.

Granite gneiss (Late Archean, 2,600-3,100+ Ma) – Layered to massive, locally migmatitic; metasedimentary and metavolcanic rocks locally common.

Metasedimentary and metavolcanic rocks – Amphibolite, hornblende gneiss, biotite gneiss, quartzite, iron-formation, metaconglomerate, marble, and pelitic schist; locally preserved textures and structures suggest origin to be sedimentary or volcanic. Older than 3,200 Ma in Granite Mountains; older than 2,600 Ma in Medicine Bow Mountains and Sierra Madre, where it is the Late Archean Phantom Lake Metamorphic Suite.

Metasedimentary and Metavolcanic rocks (Late Archean)

- Metasedimentary rocks
  - Wind River Range – Metagraywacke, pelitic schist, metaconglomerate, graphitic schist, and iron-formation; local meta-andesite. At least 2,800Ma.
  - Seminoe Mountains (southeast end of Granite Mountains) – Pelitic schist, quartzite, and iron-formation.
  - Casper Mountain (northwest extension of Laramie Mountains) – Felsic gneiss, quartzite, and iron-formation.
  - Laramie Mountains – Pelitic schist, iron-formation, quartzite, marble, metaconglomerate, and metagraywacke.

Metasedimentary and Meatvolcanic rocks (Late Archean)

- Metamorphosed mafic and ultramafic rocks
  - Bighorn and Granite Mountains – Amphibolite.
  - Seminoe Mountains – Amphibolite of volcanic origin, komatiite, and metagabbro.
  - Casper Mountain – Amphibolite and serpentinite.
  - Laramie Mountains –Amphibolite of volcanic origin, komatiite (?), metagabbro, and ultramafic sills.

Peridotite intrusive rocks (Late Archean) – In Laramie Mountains.

Symbol	*Unit Description*
p€r (cont.)	
	Granitic rocks of 2,600-Ma Age Group (Late Archean, 2,600 Ma) Sierra Madre – Granite and granodiorite. Laramie Mountains – Granite, amphibolite, and minor amounts of metasedimentary rocks. Hartville uplift – Granite and quartz monzonite.

PLATTE RIVER BASIN GEOLOGIC UNITS – COLORADO

There are 27 digital GIS geologic units in the Colorado portion of the Platte River Basin (Tweto and Schoenfeld, 1979). The stratigraphic descriptions below are taken directly from Tweto and Schoenfeld (1979) with minor modifications.

References

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States Central States – Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas, Missouri, Arkansas, and Louisiana, North Dakota, South Dakota, Nebraska, and Iowa: U.S. Geological Survey Open-File Report 2005-1351, version 1.2, updated December 2007, digital data. [Includes Wyoming, Colorado, and Nebraska at 1:500,000-scale, though different states within this database have different scales.]

Tweto, Ogden, and R. E. Schoenfeld, 1979, *Geologic map of Colorado*. [Reston, Va.]: Dept. of the Interior, United States Geological Survey, scale 1:500,000, 2 sheets.

Symbol	*Unit Description*

CENOZOIC GEOLOGIC UNITS – COLORADO

Quaternary geologic units – Colorado

Qa	Modern alluvium (Holocene) – Includes Piney Creek Alluvium and younger deposits.
Qg	Gravels and alluviums (Pinedale and Bull Lake age) (Pleistocene) – Includes Broadway and Louviers Alluviums.
Qgo	Older gravels and alluviums (Pre-Bull Lake age) (Pleistocene) – Includes Slocum, Verdos, Rocky Flats, and Nussbaum Alluviums in the east.
Qe	Eolian deposits (Holocene-Pleistocene) – Includes dune sand and silt and Peoria Loess.
Qd	Glacial drift of Pinedale and Bull Lake Glaciations (Pleistocene) – Includes some unclassified glacial deposits.
Qdo	Older glacial drift (Pre-Bull Lake age)
Ql	Landslide deposits (Holocene-Pleistocene) – Locally includes talus, rock-glacier, and thick colluvial deposits.

Symbol	*Unit Description*

Upper Tertiary geologic units – Colorado

Tgv Bouldery gravel on old erosion surfaces in Front Range and Never Summer Mountains (Pliocene (?)-Miocene)

To Ogallala Formation (Pliocene(?)-Miocene) – Loose to well-cemented sand and gravel.

Tnp North Park Formation (Miocene) – Sandstone, siltstone, and conglomerate; in North Park and Laramie basin

Tv Volcanic rock in northwestern Colorado (age <7-33 Ma) – Mainly of intermediate composition.

Tui Upper Tertiary intrusive rocks (age <20 Ma) – Intermediate to felsic compositions.

Taf Ash-flow tuff of main volcanic sequence (age 29-32 Ma) – Includes many named units.

Tmi Middle Tertiary intrusive rocks (age 20-40 Ma) – Intermediate to felsic compositions.

Lower Tertiary geologic units – Colorado

Twr White River Formation (Oligocene) – Ashy claystone and sandstone; in North Park.

Tc Coalmont Formation (Eocene-Paleocene) – Arkosic sandstone, conglomerate, and shale; coal in the lower part; in North Park.

MESOZOIC GEOLOGIC UNITS – COLORADO

Upper Cretaceous geologic units – Colorado

Kp Pierre Shale (Upper Cretaceous) – Undivided; sandstone with shale between zones of *Baculites reesidei* and *B. scotti*; organic-rich shale and numerous bentonite beds.

Kc Colorado Group (Upper & Lower Cretaceous) – Consists of Niobrara Formation (Kn) and either Benton Shale or Carlile, Greenhorn, and Graneros Formations (Kcg).
- Niobrara Formation (Upper Cretaceous) – Calcareous shale and limestone.
- Carlile Shale, Greenhorn Limestone, and Graneros Shale (Upper & Lower Cretaceous)

Lower Cretaceous geologic units – Colorado

Kd Dakota Sandstone or Group (Lower Cretaceous)

Mz Mesozoic rocks – Mainly Lower Cretaceous, Jurassic, and Triassic formations.

Cretaceous and Jurassic geologic units – Colorado

KJdm Dakota and Morrison Formations (Cretaceous & Jurassic)
- Dakota Formation (Lower Cretaceous)
- Morrison Formation (Upper Jurassic) – Variegated claystone, mudstone, sandstone, and local beds of limestone.

Symbol	*Unit Description*
KJds	Dakota, Morrison, and Sundance Formations (Cretaceous & Jurassic) Dakota Formation (Lower Cretaceous) Morrison and Sundance Formations (Upper Jurassic) – Sandstone, shale, claystone, and limestone.

Triassic geologic units – Colorado

Ꞧch	Chugwater Formation (Lower Triassic) – Red sandstone, siltstone, shale, and local limestone and gypsum.

MESOZOIC AND PALEOZOIC UNITS – COLORADO

MzPz	Mesozoic and Paleozoic rocks – Mainly as in Mesozoic unit (Mz) plus Permian and Pennsylvanian formations

Triassic and Permian geologic units – Colorado

ꞦPr	Triassic and Permian rocks (Triassic & Permian) – Red siltstone, shale, and sandstone. Includes various combinations of Nugget, Jelm, Popo Agie, Chugwater, Red Peak, Forelle, Satanka, and Goose Egg Formations near Wyoming border.

PALEOZOIC GEOLOGIC UNITS – COLORADO

Permian and Pennsylvanian geologic units – Colorado

PℙPcf	Casper Formation (Sandstone) and lower part of Fountain Formation (Lower Permian & Upper & Middle Pennsylvanian)

PRECAMBRIAN GEOLOGIC UNITS – COLORADO

pꞒr	Precambrian rocks – Proterozoic metamorphic and igneous rocks. Granitic rocks of 1,400 M.Y. age group (age 1,350-1,480 M.Y.) – Includes Silver Plume, Sherman, Cripple Creek, St, Kevin, Vernal Mesa, Curecanti, Eolus, and Trimble Granites or Quartz Monzonites; also San Isabel Granite of Boyer (1962) and unnamed granitic rocks. Granitic rocks of 1,700 M.Y. age group (age 1,650-1,730 M.Y.) – Includes Boulder Creek, Cross Creek, Denny Creek, Kroenke, Browns Pass, Powderhorn, Pitts Meadow, Bakers Bridge, and Tenmile Granites, Quartz Monzonites, or Granodiorites; also, unnamed granitic rocks. Mafic rocks of 1,700 M.Y. age group – Gabbro and mafic diorite and monzonite. Biotitic gneiss, schist, and migmatite Locally contains minor hornblende gneiss, calc-silicate rock, quartzite, and marble. Derived principally from sedimentary rocks. Felsic and hornblendic gneisses, either separate or interlayered – metabasalt, metatuff, and interbedded metagraywacke; locally contains interlayered biotite gneiss. Derived principally from volcanic rocks.

Appendix B

WWDC Groundwater Studies

Brett Worman, and Karl Taboga

Appendix B WWDC Groundwater Studies.

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Wyoming. Water Planning Program, 1973, Wyoming's groundwater supplies: Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, variously paged.	Wyoming	All	Summary of available groundwater and groundwater sources.	Predictions of aquifer water quantity throughout the state of Wyoming.	N/A
Wyoming Water Planning Program, 1974, Groundwater potential of the Arikaree Formation in the Sweetwater drainage (Fremont, Natrona, and Carbon Counties, Wyoming): Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, variously paged.	Fremont Natrona Carbon Counties	Arikaree	Reconnaissance investigation of the State's groundwater resources in the Arikaree formation near the Split Rock area.	Large volumes of water removed from the aquifer could alter the Sweetwater River.	N/A
Crist, M.A., 1975, Hydrologic analysis of the valley-fill aquifer, North Platte River valley, Goshen County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 75–3, 60 p., 4 pls.	Goshen County	Ogallala, Arikaree, Brule, Chadron, Lance Formations	Quantitative evaluation of groundwater in the valley fill, and surface water in the North Platte River Valley.	Contains estimates of the amount of groundwater resources	N/A
Anderson and Kelly, Inc., 1982, Hydrogeologic evaluation of the Casper aquifer (drilling program number 1) Albany County, Wyoming: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Casper Aquifer	Hydrologic Evaluation; Drilling of exploratory wells, pump testing production, analysis of pump testing data and water quality	Formation has good aquifer potential; water quality degrades toward Cretaceous rocks. Future development from the test location is limited to stock water.	N/A
Black & Veatch, 1982, Hanna, Wyoming, Wyoming Water Development Commission ground water exploration program progress report: prepared for the Wyoming Water Development Commission, variously paged. Black and Veatch, 1983, Hanna, Wyoming groundwater exploration program, Wyoming Water Development Commission exploratory drilling report: prepared for the Wyoming Water Development Commission, variously paged. Black and Veatch, 1984, Hanna, Wyoming report on water resource development alternatives: prepared for the Wyoming Water Development Commission, variously paged.	Town of Hanna	North Park, Frontier Formations	Examination of possible sources to meet the increasing industrial demand, and investigations of drought constrains on current supply.	Further study is recommended concerning surface water supply for future water demand. Water produced from test wells does not meet EPA water quality standards.	Alternatives of drilling wells for increased water supply was not recommended as well use would likely result in aquifer mining and will not provide a long term solution.
Howard Needles Tammen & Bergendoff, 1982a, Level II feasibility study, water supply for Town of Encampment, phase 1 status report; evaluate existing water supply: prepared for the Wyoming Water Development Commission, variously paged. Howard Needles Tammen & Bergendoff, 1982b, level II feasibility study, water supply for Town of Encampment, phase 2 status report, identify and prioritize additional water supply alternatives: prepared for the Wyoming Water Development Commission, variously paged.	Town of Encampment	North Park Formation	Phase I and II status report to evaluate the existing water supply to the town of Encampment	A well field located north of town could supply water to meet the needs of the town of Encampment producing 59 million gallons over a 92 day period. Radionuclides exceed levels allowed by drinking water standards.	Investigation into the feasibility of alternatives based on low capacity and radionuclide problems.

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Howard, Needles, Tammen, and Bergendoff, 1984, in association with Simons, Li, and Associates, Inc., Water supply for Town of Encampment final report, level II feasibility study: prepared for the Wyoming Water Development Commission, variously paged.					
James M. Montgomery, Consulting Engineers, Inc., 1982a, in association with Anderson and Kelly, City of Rawlins, Wyoming hydrogeologic and water supply study task report No. 1, phase I: prepared for the Wyoming Water Development Commission, 13 p., 1 pl.	City of Rawlins	North Park, Battle Spring, Fort Union, Lance, Mesaverde, Frontier, Cloverly, Tensleep, Madison Formations and Cambrian System	Task Report No. 1, Phase I, is to identify ground water source areas near Rawlins where further evaluation is needed and to eliminate source areas with little or no development potential.	Lance, Fort Union, and Battle Spring Formations are recommended for further evaluation based on quantity and quality of water. The Madison Formation may be cost prohibitive unless production exceeded 500-1,000 gpm.	Recharge to the Battle Spring Formation is meteoric, which may limit recharge. Further study of the area is recommended.
James M. Montgomery, Consulting Engineers, Inc., 1982b, City of Rawlins, Wyoming hydrogeologic and water supply study task report No. 2, phase II, III, IV: prepared for the Wyoming Water Development Commission, variously paged.	City of Rawlins	North Park, Battle Spring, Cloverly, Tensleep, Madison Formations	Results of Task Report No. 2, Phase II, III, and portions of Phase IV of the hydrogeologic water supply study for Rawlins. An evaluation of potential sources of groundwater in the Rawlins area.	Ranked in order of development potential are the Paleozoic formations, North Park Formation, Battle Spring Formation, and the Cloverly Formation.	Experimental test drilling of the Paleozoic sediments underlying the Sage Creek Basin is considered to be warranted.
MSM Consultants, 1982, in association with Willard Owens Associates, Inc., Town of Evansville groundwater availability study, vicinity of Evansville, Wyoming: prepared for the Wyoming Water Development Commission, variously paged.	Natrona County	Cloverly Formation Casper aquifer Madison aquifer	Investigate possible solutions to satisfy future increased water demands through groundwater for the town of Evansville. Develop test wells and relate the results to future water needs.	Groundwater is considered the only new source of potable water. Test wells yield 100-300 gpm with higher yield possible. Total dissolved solid concentration remain under 500 mg/L	Further testing of the Cloverly Formation for higher yield and better water quality.
Nelson Engineering, 1982, A plan to drill and test a water well south of the Town of Glenrock, Wyoming: prepared for the Wyoming Water Development Commission and the Town of Glenrock, variously paged.	Town of Glenrock	Deer Creek Alluvium Casper Formation	Investigate groundwater sources to increase the town of Glenrock's available water supply during peak demand.	Identified locations for wells to be drilled into the Casper formation.	Proceed with drilling and testing program for wells at the identified locations.
Simons, Li, and Associates, 1982a, Riverside groundwater resources investigation and development, final report: prepared for the Wyoming Water Development Commission, variously paged. Simons, Li, and Associates, 1982b, Riverside groundwater resources investigation and development, interim report: prepared for the Wyoming Water Development Commission, variously paged.	Town of Riverside	North Park Formation	A groundwater resources investigation and development report for the town of Riverside. Collection of information on local major aquifers and development of a potable groundwater supply.	The gravel, sand, and clay are discontinuous through the exploration zone. Water quality corresponds with rock type. Depth to the Precambrian boundary is highly variable with water levels dependent on fractures and faulting.	N/A
Western Water Consultants, Inc., 1982, Ground water development potential of the Paleozoic aquifer along the flanks of the Laramie Range and Hartville Uplift, southeastern Wyoming: prepared for the Wyoming Water Development Commission, 88 p., 8 pl.	Laramie County	Paleozoic aquifer	Reconnaissance level evaluation of potential groundwater development from the Paleozoic rocks surrounding the Laramie Mountain-Casper Mountain ranges and Hartville Uplift.	Best quality and quantity of groundwater was found in the Casper/Tensleep and Madison formations.	N/A

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Banner Associates, Inc., 1983, Feasibility study for groundwater development for the Town of Medicine Bow, prepared for the Wyoming Water Development Commission, variously paged.	Town of Medicine Bow	Casper aquifer	Determine sources for water to sustain increased future demand.	Shut down Como #3 Well due to contamination in the upper most sand of the aquifer.	Investigate water treatment, develop a new source, improve Como well #3, and construct a new deeper well at same location.
Black & Veatch, 1983, Water Supply Needs Assessment for the North Platte and Little Snake River Drainages Phase I, Vols. 1,2: prepared for the Wyoming Water Development Commission, variously paged.	North Platte and Little Snake River Drainages	N/A	Phase I, Volumes I & II, analysis of the water supply needs of various communities located within the North Platte and Little Snake River Conservation District.	There is the possibility to develop enough water to meet both in basin and out of basin needs for the near future	Continue with Phase II of the Water Supply Needs Analysis.
Hydro-Search, Inc., 1983, Bairoil, Wyoming Groundwater Development Feasibility Exploration Program Design: prepared for the Wyoming Water Development Commission, variously paged.	Town of Bairoil	Quaternary Alluvium Fox Hills, Lance, Fort Union, and Battle Spring Aquifers	Determine feasibility of groundwater development to supplement current and future demand for the town of Bairoil.	Lance and Fox Hills aquifers are not feasible due to limited saturated thickness and/or low permeability. Battle Spring and Fort Union aquifers are capable of supplying adequate amounts, Battle Spring aquifer is considered to be the more viable source.	Adequate groundwater sources exist in the vicinity of Bairoil for municipal development, an exploration program is recommended.
James M. Montgomery, Consulting Engineers, Inc., 1983a, City of Rawlins water development master plan: prepared for the Wyoming Water Development Commission, 2 v., variously paged. James M. Montgomery, Consulting Engineers, Inc., 1983b, in association with Anderson and Kelly, Inc., Section I, City of Rawlins hydrogeologic investigations for water supply development final report, *in* James M. Montgomery, Consulting Engineers, 1983, City of Rawlins water development master plan volume II, background data and reports: prepared for the Wyoming Water Development Commission, variously paged.	City of Rawlins	North Park, Battle Spring, Cloverly, Nugget and Tensleep Formations	Water Development Master Plan V. I and II, for evaluating sources of water to supplement current water supply for the town of Rawlins.	Cloverly formation has the greatest potential for water development. With 100-150 gpm yields of good water quality. Nugget wells are also producing groundwater in adequate supplies and quality. Remaining aquifers do not have the necessary characteristics for production scale water levels.	Moving forward with drilling and testing of production scale wells.
No author, 1983, Municipal Water Supply Source Problems, Town of Medicine Bow, Wyoming: prepared for the Wyoming Water Development Commission, variously paged.	Town of Medicine Bow	N/A	Feasibility study to determine most usable option to correct the town of Medicine Bow's water quality issues.	Drill and test a small diameter monitor well. Drill and test a production sized well according to Banner Associates original design. Drill and test production sized well incorporating University of Wyoming design.	N/A
Morrison-Maierle, Inc., 1984a, Casper aquifer drilling program No. 2 with results of aquifer tests, final report: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Casper and Madison Aquifers	Level II feasibility study to develop information on the productivity of the Casper Aquifer system.	Wells drilled into the Casper Aquifer yielded water from zones of secondary fracture and encountered artesian pressure at the Casper-Madison contact. Pump test resulted in 104 gpm pumping rates. Transmissivity of 38,098 gpd/ft and storativity of 0.037.	N/A

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Anderson and Kelly, Inc., 1984, Hydrogeologic evaluation of the Nugget aquifer near Rawlins, Wyoming level II feasibility study: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	Nugget Aquifer	Hydrologic evaluation of aquifer feasibility for supplemental water supply for Rawlins municipal supply	Well could yield 1.5 million gpd, water quality does not meet EPA standards for TDS.	Recommendation for development of Nugget Sandstone for municipal supply
Banner Associates, Inc., 1984, Construction and testing of the Como No. 4 well: prepared for the Town of Medicine Bow and the Wyoming Water Development Commission, variously paged.	Town of Medicine Bow	Casper Aquifer	Drilling and testing phase of the Como #4 Well to replace the Como #3 Well due to radioactive contamination.	Como #4 Well water quality and pump rates were found to be satisfactory. The water producing zone between 580 and 660 feet has high levels of radium present in samples.	N/A
Black & Veatch, 1984, in association with Wright Water Engineers Inc., Water supply needs assessment for the North Platte and Little Snake River drainages Phase II: prepared for the North Platte Water Development Joint Powers Board, variously paged.	Platte and Little Snake River drainages	Various aquifers and surface water	Phase II, Analysis of the municipal, agricultural, and industrial water supply needs within the North Platte and Little Snake River drainages. Investigate the ability of the water users to pay for additional water supplies.	There is a need for additional municipal water supplies in both the North Platte and the Little Snake River Basins; however the amount varies greatly based on water supply assumptions.	N/A
Morrison-Maierle, Inc., 1984b, Glendo groundwater exploration program feasibility study: prepared for the Wyoming Water Development Commission and the Town of Glendo, variously paged.	Town of Glendo	Hartville Formation	Exploration program to determine supply needs for current and future water demands for the town of Glendo.	The current system is capable of providing supply for peak summer consumption. Future needs cannot be met by this rate of extraction.	Replace transmission line with a larger capacity line or provide adequate storage for peak use times.
James M. Montgomery, Consulting Engineers, Inc., 1986b, Rawlins groundwater project level III, Nugget Aquifer report: prepared for the Wyoming Water Development Commission, variously paged.	City of Rawlins	Cloverly and Nugget Formations	Level III Interim/Summary Report to aid in a detailed evaluation of improvements to the city of Rawlins existing water supply.	Wells in the Nugget Sandstone exceeded minimum secondary standards for TDS and sodium concentration. Shut in, the well maintains a 140 psi pressure and a discharge of 350 gpm.	Implement plans and findings of Level III report. Limit storage requirements, maintain groundwater supply, reduce use of existing North Platte water supply, and properly size Sage Creek Water transmission line.
James M. Montgomery, Consulting Engineers, Inc., 1986a, Rawlins groundwater project level III, interim report: prepared for the Wyoming Water Development Commission, variously paged.	City of Rawlins	Nugget Aquifer	Rawlins Groundwater Project Level III, Nugget aquifer report gives detail for recovery rates of the test wells into the Nugget Sandstone and details need for future wells to meet future demand.	Nugget Wells No. 2 and 3 drilled to depths of 1,743 and 1,625 ft respectively with short-term flows of 900 and 80 gpm. Long-term recovery tests show flows of 650 and 80 gpm respectively. Long-term flow was increased from 80 gpm to 400 gpm after hydraulic fracturing of Well 3.	Examination of further well sites at three identified locations is recommended to increase maximum flow rates. Also recommends hydrologic fracturing to increase the flow rate in any new wells.
Nelson Engineering, 1986, Glenrock water supply design report: prepared for the Town of Glenrock and the Wyoming Water Development Commission, variously paged.	Town of Glenrock	Casper Aquifer	Report contains an operating plan for new water supplies, conceptual design for facilities, and a summary of findings from hydrological investigations for the town of Glenrock.	Well design capacity should be at least 600 gpm. Water quality is similar to that of neighboring wells. No reduction of stream flow was observed during pumping of the well.	Project was determined to be feasible and suitable.

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Wyoming Water Development Commission, 1986, Casper aquifer exploration program summary report: Cheyenne, Wyoming Water Development Commission, 13 p.	Southeast Wyoming	Casper Aquifer	Program report to determine the quality, quantity, and availability of water within the Casper aquifer.	Areas tested show high capacity and good quality water in the aquifer within a relatively short distance from the recharge area, and also where permeability has been enhanced due to deformation or solution activity.	A more detailed description of the results can be found in individual reports.
Anderson and Kelly, Inc., 1987, Hydrogeologic evaluation of the Natural Bridge well, Converse County, Wyoming: prepared for ARIX Corporation, variously paged.	Converse County	Casper aquifer	Evaluate well potential maximum pumping and usage rates	Total available drawdown of 129 feet which will occur in 9.8 years with continuous use.	Recommendation for non-continuous usage to alleviate potential for maximum drawdown
Centennial Engineering & Research, Inc., 1989, Ridgewater Water Supply Project Level II, Phase I Report: prepared for the Wyoming Water Development Commission, variously paged. Centennial Engineering and Research, Inc., 1991, Ridgewater water supply project level II, final report: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	White River Formation	Level II, Phase I and Final Report evaluation of groundwater supply and quality from an exploratory well for the City of Douglas and Ridgewater Improvement and Service District.	The city of Douglas would own, operate, and maintain the 1,200 gpm of treated water distributing it to the city and the Ridgeway District. This water supply would be sufficient to service rural users.	All water issues should be dealt with according to the signed agreement between the two parties.
James M. Montgomery, Consulting Engineers, Inc., 1989, Centennial water supply project report: prepared for the Wyoming Water Development Commission and the Centennial Water and Sewer District, variously paged.	Albany County	Casper Formation	Centennial Water Supply Project and Executive Summary was commissioned to determine water supply sources for the community of Centennial.	Based on all necessary criteria, bedrock groundwater is the most suitable source to expand the current water supply. Long term yield of 40 gpm, high water quality, and no conflicting water use.	Provided that funding can be secured, construction based on the design within the report should be carried out.
James M. Montgomery, Consulting Engineers, Inc., 1990b, Natrona County regional water system project level I: prepared for the Wyoming Water Development Commission, variously paged.	Natrona County	Casper aquifer Madison aquifer	The Evansville Groundwater Supply Project Final Report was commissioned in an attempt to determine if groundwater is a viable source for the municipal water supply.	The current water supply needs of the town of Evansville are adequate for the estimated population for 50 years.	Concerns for future water supply revolve around prior appropriation of currently used surface water. If surface water rights are claimed, groundwater will provide a more secure source.
James M. Montgomery, Consulting Engineers, Inc., 1990c, Report of drilling and testing Rolling Hills well No. 5: prepared for the Wyoming Water Development Commission and the Town of Rolling Hills, variously paged.	Converse County	Fort Union/Lance aquifer	Drilling and testing report for the Rolling Hills No. 5 well summarizes findings from afore mentioned well. Groundwater supplies from previous wells were no longer sufficient and further resources are needed.	Development potential of the aquifer is most likely deeper in the formation as the sands are more laterally continuous. Water from the well meets all EPA standards for primary water. Production capacity of 96 gpm was projected.	Completion of the Level II report

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
PMPC, 1990, Level II analysis Riverside area municipal water supply system Town Riverside, Carbon County, Wyoming, interim report: prepared for the Wyoming Water Development Commission, variously paged. PMPC, 1992, Level II analysis Riverside municipal water supply system, Town of Riverside, Carbon County, Wyoming, volume I, final report and volume II, technical appendix: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation	Determine the feasibility of creating a municipal water supply system from the existing individual owner-wells for the town of Riverside.	A well field consisting of a minimum of three wells with the possibility to add more.	Recommended to go ahead with the formation of a municipal water system.
States West Water Resources Corporation, 1990, in association with ESA Consultants, Crow Creek groundwater recharge project, level II: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Alluvial deposits Terrace deposits Ogallala Formation White River Formation	Phase IB of Level II feasibility evaluation of the Crow Creek flood control and groundwater recharge project. Examining recharge of the groundwater system in the Carpenter Wyoming area.	Conditions are favorable for the implementation of an experimental groundwater recharge in the vicinity of Carpenter.	N/A
TriHydro Corporation, 1990b, Ridgewater water supply project level II, phase II report: prepared for Centennial Engineering and Research and the Wyoming Water Development Commission, variously paged.	Converse County	Casper Formation	Level II, Phase II study to determine the feasibility of developing groundwater in sufficient quantity and quality to meet future domestic and fire-protection requirements of Ridgewater.	Groundwater quality is of acceptable quality for municipal use. Maximum pump rate of 1,039 gpm. Seven day pumping average of 1,001 gpm. Conductivity of 1,715 gpd/ft^2, and a transmissivity of 574,660 gpd/ft.	.N/A
TriHydro Corporation, 1990a, Construction and testing report Yoder No. 2 production well, Yoder, Wyoming: prepared for Wells Engineering, variously paged.	Goshen County	Brule Formation	Exploration phase to increase the quality and quantity of water to satisfy the water requirements of the town of Yoder, Wyoming	Based on aquifer parameters, it is recommended that a groundwater management plan including a well field be implemented to meet the demands of the town of Yoder	N/A
Coffey Engineering and Surveying, Inc., 1991, in association with James M. Montgomery, Consulting Engineers, Ryan Park water supply project final report, water supply alternatives level I: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	Quaternary Alluvium Tertiary Alluvium Precambrian	Development of a conceptual design for a water supply system of the unincorporated community of Ryan Park.	Four sites have been identified for further studies of groundwater exploration or development. The Barrett Creek Site was identified after consultation with WWDC and location owner. The Ryan Park Deep Well Site was also identified as a possibility.	Formation of an official district and proceed with a level II study
Snowy Range Water Consultants, Inc., 1991, South Laramie water supply project level I, final report: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Casper aquifer	Evaluate the potential for providing potable water to the South Laramie vicinity in Albany County.	Construction of two wells a mile apart along the Laramie fault that can be readily incorporated into the city system at a later date.	N/A
States West Water Resources Corporation, 1991, Upper Laramie River basin planning study, level I investigation: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Tertiary aquifer Cloverly aquifer Casper-Tensleep aquifer	Level I planning study, evaluation of alternatives for supplying late-season irrigation water to the Irrigation district, and reduction of reservoir storage losses for the Pioneer Canal-Lake Hattie district.	Alternatives to the current water use program do not include the utilization of ground water.	Move forward with a Level II study

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
James M. Montgomery, Consulting Engineers, Inc., 1992, Centennial water supply project report, 1990 Centennial wells No. 1 and 2 aquifer testing: prepared for the Wyoming Water Development Commission and the Centennial Water and Sewer District, variously paged.	Albany County	Casper aquifer	Aquifer testing for wells No. 1 and 2 for the Centennial water supply project.	Development from the Casper aquifer does not affect nearby surface water. Pumping rates in wells exceeded 150 gpm. Water quality from both wells is within criteria set for primary and secondary EPA standards	N/A
States West Water Resources Corporation, 1996, in association with Chugwater Enterprises, and Wester-Wetstein and Associates, Inc., Town of Chugwater water supply master plan level I project: prepared for the Wyoming Water Development Commission, variously paged.	Platte County	Tertiary aquifer	Level I reconnaissance investigation to develop a water supply master plan for the North Cheyenne area.	Development has affected the chemical quality of water in North Cheyenne, no sample exceeded EPA standards. However, the proposed EPA standard for radon was exceeded in three of the four wells sampled. A distribution system with a water supply from the city of Cheyenne is recommended.	.N/A
AVI Professional Corporation, 1994, Pine Bluffs level I water study: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Brule Formation	Evaluate existing water supply to determine any deficiencies for the town of Pine Bluffs.	Static water levels in existing wells have dropped and average of 4 feet in 15 years. Ground water may be under influence from surface contamination.	Production capacity must be tested with long term constant discharge testing.
Baker and Associates, 1994, Wellhead protection program, Torrington, Wyoming; chapter III ground water investigation monitoring wells and chapter IV ground water monitoring results: prepared for the Wyoming Water Development Commission, variously paged.	Goshen County	Brule Formation	Determine the source of nitrate contamination in the municipal water supply of Torrington.	Nitrate contamination comes dominantly from agricultural and urban fertilization, feedlot, and chemical storage sources.	Relocation of wells to less contaminated areas and management programs limiting nitrate entering groundwater systems.
Black and Veatch, 1994, in association with Western Water Consultants, and Wester -Wetstein and Associates, Cheyenne water supply master plan level I: prepared for the Wyoming Water Development Commission and the Cheyenne Board of Public Utilities, 3 v., variously paged.	Laramie County	Casper Formation	Assist the Cheyenne Board of Public Utilities in developing strategies concerning future water supply, treatment, and distribution systems.	Groundwater supplies are sustainable at a pumping rate of 5,500 acre-feet per year, which is the limit imposed by the State Engineers Office.	The Casper Formation offers the opportunity to develop additional groundwater in the vicinity of the existing facilities. Recommendation for exploration programs in target areas.
PMPC, 1994, Level II analysis Ryan Park water supply project Ryan Park, Carbon County, Wyoming, final report: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation Precambrian	Determine an adequate source for the recommended community water supply system in Ryan Park.	Recommend drilling wells to meet the demand of 72 gpm.	N/A
Worthington, Lenhart, and Carpenter, 1994, Town of Lusk water project level I master plan study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Niobrara County	Arikaree aquifer	Level I study to determine future water needs relative to current supplies for the municipal water supply district of Lusk.	Drilling of an additional well will satisfy demand until 2020.	N/A

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Coffey & Associates, 1995, Corner Mountain water supply project, water supply alternatives, level I, final report: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Cloverly Formation Casper Formation	Level I feasibility study for a conceptual design of water supply for the Corner Mountain area.	Deep water wells are expected to fill the current and future needs of the land owners. Cloverly Formation wells are expected to yield 50-100 gpm. Casper Formation sites are expected to yield 30-50 gpm.	Recommendation for the formation of a water district. Landowners need to compare the cost of drilling a well and continued maintenance versus the fees associated with joining a water district.
Lidstone and Anderson, 1995, in association with AVI, P.C., Final report, Town of Pine Bluffs water supply project level II: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Brule aquifer	Level II study to determine cause of declining water production for the town of Pine Bluffs, define characteristics of aquifer used, and meet demand and legal requirements with increased production.	Projected drawdown after 20 years of pumping from the field showed a maximum of 2 feet in the center to 1.5 feet at the nearest irrigation well. This drawdown shows sufficient supply for current and future needs.	N/A
MK Centennial, 1995, Lusk water supply project level II Lusk, Wyoming, final report: prepared for the Wyoming Water Development Commission, variously paged.	Niobrara County	Arikaree Formation	Construct an additional water supply well and prepare conceptual designs and cost estimates for improvements to the existing system.	The predominantly sandstone with coarse basal conglomerate of the Arikaree Formation yielded 1,000 gpm during pump tests.	Final well development was completed at the end of this phase.
TST Inc., 1995a, in association with Rio Verde Engineering, and Weston Engineering, Guernsey water supply master plan, level I final: prepared for the Wyoming Water Development Commission, variously paged.	Platte County	Quaternary Sediments Tertiary Sediments Hartville Formation Darwin Sandstone Madison Formation Freemont Canyon Sandstone Precambrian	Determine the condition, storage, transmission, and remaining useful life of the water supply and distribution system for the town of Guernsey.	Production of 550 and 1,000 gpm pumping rates for current wells. Recommended that the town complete a fourth well to replace inefficient wells. Concentration of iron and manganese exceed the secondary water standards. Groundwater potential from Paleozoic rocks in the area is poor.	N/A
Weston Engineering, Inc., 1995a, Elk Mountain water supply master plan, level I report: prepared for the Wyoming Water Development Commission and the Town of Elk Mountain, variously paged. Weston Engineering, Inc., 1995b, Elk Mountain water supply project, level II final report: prepared for the Wyoming Water Development Commission and the Town of Elk Mountain, variously paged.	Carbon County	Dakota Sandstone Lakota Sandstone	Level I and II reports for the town of Elk Mountain water district to evaluate the current water distribution facilities and sources.	Construction of a new well into the currently used aquifer to produce the necessary water to supply municipal needs.	N/A
BRS Inc., 1996, in association with Lidstone and Anderson, Inc., Hawk Springs water supply project, final report: prepared for the Wyoming Water Development Commission, variously paged.	Goshen County	Arikaree Formation Lance Formation	Determine the feasibility of creating a community water and waste water treatment system.	The Lance Formation in the area is not suitable for drinking water.	The district must be able to provide service to at least 30 to 35 taps for the project to be feasible.

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
States West Water Resources Corporation, 1996, in association with Chugwater Enterprises, and Wester-Wetstein and Associates, Inc., Town of Chugwater water supply master plan level I project: prepared for the Wyoming Water Development Commission, variously paged.	Platte County	Brule Formation	Level I reconnaissance investigation to develop a water supply master plan for the town of Chugwater.	Proposed locations of two new wells into the existing aquifer, located in either the current well field or next to the storage tank. Flow rate of 157 gpm, static water level of 34.15 feet.	Proceed with Level II study.
TriHydro Corporation, 1996, Well construction and aquifer testing level II water supply project, Lusk, Wyoming, final report: prepared for the Wyoming Water Development Commission and Centennial Civil Engineers, Inc., variously paged.	Niobrara County	Arikaree Formation	Level II study to determine new sources of groundwater to replace outdated and degrading water supplies and systems for the town of Lusk.	A minimum of four wells with average production rates of 819 gpm would be needed to supply future demands for the town of Lusk, Wyoming.	N/A
TriHydro Corporation, 1996, Level II water supply project, Rolling Hills, Wyoming, final report: prepared for the Wyoming Water Development Commission and the Town of Rolling Hills, variously paged.	Converse County	Fort Union Formation Lance Formation	Level II project to evaluate the feasibility of increasing the supply to the town of Rolling Hills, Wyoming.	Water quantity and quality from the Lance Formation is within the limits and requirements. Aquifer mining is a concern.	Install and test the Rolling Hills No. 6 well to evaluate the feasibility of increasing the water supply.
PMPC, 1997, Final report, level II feasibility study, Encampment water supply system: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation	Level II feasibility study for the town of Encampment's community water supply system.	The town has the sufficient rights to acquire all water needed form the North Fork Encampment River.	N/A
Western Water Consultants, 1997, Final report on the Manville water supply project level II, Volumes I and II: prepared for the Wyoming Water Development Commission, variously paged.	Niobrara County	Arikaree aquifer	Level II project to evaluate the groundwater supply and existing wells for the town of Manville.	Groundwater quality from the aquifer is considered excellent and is the best source of water for the municipality.	Proceed with completion of required aspects of the WHP plan and preparing a contingency plan.
Western Water Consultants, Inc., 1997, in association with Richard P. Arber Associates, City of Rawlins water supply project level II, phase I report: prepared for the Wyoming Water Development Commission, variously paged. Western Water Consultants, Inc., 1998, in association with Richard P. Arber Associates, City of Rawlins water supply project level II, phase II report: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	Nugget Sandstone	Level II water supply project of the water supply system for the town of Rawlins.	A current supply deficit will be made up using supply from the North Platte River surface water source.	Plan to improve delivery from the surface water source.
Benchmark of Torrington, P.C., 1998, Town of Lingle water supply master plan level I project, final report: prepared for the Wyoming Water Development Commission, variously paged.	Goshen County	Quaternary Alluvium	Investigation into development of a water supply plan for the town of Lingle.	The current storage and supply network for the town of Lingle sufficient to support growth for the foreseeable future.	N/A
CH2M Hill, 1998, in association with States West Water Resources Corporation, Cheyenne aquifer storage recovery test project: prepared for the City of Cheyenne and the Wyoming Water Development Commission, variously paged.	Laramie County	Ogallala Formation White River Group Lance Formation Fox Hills Sandstone	Test drilling program to investigate the geology, hydraulic properties, and water quality at three locations in the Cheyenne area.	Costs an expected to exceed other water supply options in the Cheyenne area. Continued rehabilitation of wells should occur in the Happy Jack Well Field as they have a potential for applications.	N/A

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Coffey & Associates, 1998, in association with Banner & Associates, Inc., Nine Mile water supply project level I, final report: prepared for the Wyoming Water Development Commission, variously paged. Western Water Consultants, 1999, Report of the level II study for the Nine Mile Water and Sewer District: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Quaternary Alluvium Frontier Formation Cloverly Formation Casper Formation	Level I and II studies exploring alternatives to the current method of water acquisitions for residents in the Nine Mile development west of Laramie.	Water within the shallow unconfined aquifer is not acceptable as a potable water source. Water has a higher than adequate TDS and sulfate concentration. Suitable water can be obtained from deeper, confined aquifers.	Via options for water supply is from the municipal water supply from the city of Laramie.
Sear-Brown Group, 1998, City of Douglas Water System Master Plan Level I: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Casper Formation	A Level I Water System master Plan to evaluate and provide recommendations concerning the town of Douglas's raw water supply.	Replacement of existing facilities should be evaluated.	N/A
Sunrise Engineering and Weston Engineering, Inc., 1998, Glenrock raw water irrigation project level II study, phase 1: prepared for the Wyoming Water Development Commission, variously paged. Sunrise Engineering and Weston Engineering, Inc., 2000, Glenrock water source project level II study, phase II, final report: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Casper Formation Madison Limestone Flathead Sandstone	Level II water supply study for the town of Glenrock. Test well drilling, field evaluation, and modeling of the distribution system.	Maximum pump rate of 1,200 gpm with both the Casper and Madison Formations being utilized. Water quality does not exceed any DEQ standards.	N/A
Civil Engineering Professionals, Inc., 1999, in association with West Plains Engineering and Weston Engineering, Final Report, Douglas water supply rehabilitation project level II study: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Quaternary Alluvium	Determine if the groundwater supply is influenced from surface waters in a zone of current and future development.	Spring flow experiences seasonal flow variation which coincides with spring snow melt. ^{14}C samples indicted that the water from the spring is ~1,620 years old. Conclusions are that the ground water is not under direct influence from surface water.	Complete source water protection plan was recommended by the report authors.
Coffey & Associates, 1999, in association with Weston Engineering, Corner Mountain water supply project level II, final report: prepared for the Wyoming Water Development Commission, variously paged. Coffey & Associates, 2001, in association with Weston Engineering, Corner Mountain Water Supply Project Level II, Phase III: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Cloverly Formation Casper Formation	Level II feasibility study for a conceptual design for water supply for the Corner Mountain area water users.	Target aquifers were not encountered during drilling but logging identified several possible water-bearing strata. Further testing of the Cloverly Formation is recommended, cost is within range of user finance.	N/A
Lidstone and Associates, Inc., 2000, Bairoil water supply project level II, final report: prepared for the Wyoming Water Development Commission, variously paged. Lidstone and Associates, Inc., 2001, Bairoil water supply project level II, phase IV, final report: prepared for the Wyoming Water Development Commission, variously paged.	Sweetwater County	Battle Spring aquifer Fort Union Formation	Level II study to evaluate the current system and make recommendations for the development of a long term reliable water supply source for the municipality of Bairoil.	Alternative groundwater supplies are two from the Quaternary alluvium or colluviums aquifer and two alternatives would utilize a deep Tertiary groundwater source in the Fort Union Formation.	Utilization of the Battle Spring aquifer well is recommended.

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Lidstone and Associates, Inc., 2003, Town of Bairoil water supply project level II, phase V report: prepared for the Wyoming Water Development Commission, variously paged.					
Dahlgren Consulting, Inc., 2001, in association with Natural Resources Consulting Engineers, Hydrokinetics and ECI, Lodgepole Aquifer storage and retrieval level I study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	White River Formation	Feasibility of aquifer storage and retrieval technologies in the Lodgepole Creek Basin.	Quaternary materials and alluvium appear to provide a medium for recharge. Water from Chivington and Durham well fields would be compatible with current aquifer water.	The ASR project is not feasible at this time due to the cost of water supply and transmission.
Banner Associates, Inc., 2002, Powder River water supply level I study: prepared for the Wyoming Water Development Commission, variously paged.	Natrona County	Quaternary Alluvium Frontier Formation Cloverly Formation	Identify water treatment options available to residents and/or develop an alternate water source for residents of Powder River.	Install centralized or point-of use reverse osmosis treatment systems, locate a new source of supply.	A five mile radius of economic feasibility was determined for future wells. Samples were collected in an attempt to correlate geology.
CEPI, 2002 , South Garden Creek water supply level I study: prepared for the Wyoming Water Development Commission, the Central Wyoming Regional Water System and the City of Casper, variously paged.	Natrona County	Quaternary Alluvium Lakota Sandstone	Evaluate methods of providing public water supplies to serve the developments within the study area to supplement groundwater.	Supply options were determined for each zone within the South Garden Creek area of Casper.	N/A
Lidstone and Associates, Inc., 2003, Town of Pine Bluffs ground water exploration grant final report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Brule aquifer Chadron Formation Lance Formation	Final Report to determine a suitable replacement for the towns existing well #5 as it has decreased in production in association with drought.	Two suitable sites were located, both into the Brule aquifer, having 300 and 700 gpm pumping rates. Exploration of the Lance formation resulted in the determination that it would be a suitable aquifer yielding 50-100 gpm.	Recommendation for further exploration of the Lance/Fox Hills test sites with deeper wells.
PMPC, 2003, in association with TST Inc., Hinckley Consulting, and Water Right Services, Saratoga master plan update and level I study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation	Level I study evaluating the current system, estimation of future system needs, and groundwater as an alternative for future needs.	Identification of two suggested exploration sites to evaluate the North Park Formation. Water quality is not expected to increase with depth so well(s) should be drilled to the threshold water quality depth.	Pursuit of a Level II groundwater investigation program.
TST Inc., 2003, in association with AVI, Guernsey hydraulic study level II, final report: prepared for the Wyoming Water Development Commission, variously paged.	Platte County	Hartville Formation Madison Formation Precambrian	Level II study evaluating the pending groundwater disinfection rules and the ability of the current system to meet those needs. Determine the condition and remaining useful life of the water supply, storage and transmission system for the town of Guernsey.	All incidences of contamination were reported as isolated incidences, not regular or continued issues. Need for an alternate water supply source closer to point of use. Access to water source is inaccessible during some times of the year and after incidences.	N/A

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Lidstone and Associates, Inc., 2004, Platte Goshen regional master plan level I study: prepared for the Wyoming Water Development Commission, 93 p.	Platte and Goshen County	Quaternary aquifers Tertiary aquifers Paleozoic aquifers	Investigate the feasibility of developing a regional water supply system for several communities within the two counties to dampen costs of compliance with current EPA standards.	Groundwater alternatives require new well fields at Hartville, Dwyer, Kelly Park, Caber and Wycross prospect locations with storage at Guernsey, Lingle, and Hawk Springs in order to serve all communities within the study area.	N/A
TriHydro Corporation, 2004, in association with Lidstone and Associates, Inc., Task 7 groundwater exploration programs, Split Rock and Shirley Mountains groundwater prospects, North Platte River groundwater assessment study project report: prepared for the Wyoming Water Development Commission, variously paged. TriHydro Corporation, 2007, Project report Split Rock groundwater development project phase IV feasibility study for pumping stations and pipeline to Casper: prepared for the Wyoming Water Development Commission, variously paged.	Platte River Basin	Ogallala Formation Arikaree Formation Split Rock Formation White River Formation	Investigation into the available groundwater resources of the North Platte River Basin and adjacent areas of Wyoming. Task 7 details the design of the exploration program.	Aquifer and water quality testing in the vicinity of Split Rock and the Shirley Mountains within the Platte River Basin.	N/A
Benchmark Engineers, P.C., 2005, in association with Dahlgren Consulting, Inc., and WWC Engineering, Town of Albin well and water supply study level II: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Ogallala aquifer Arikaree aquifer White River aquifer	Evaluate current water supply system and make recommendations for improvements to meet future demand.	New wells should be constructed into the Ogallala aquifer south of Albin.	N/A
Dahlgren Consulting, Inc., 2005, in association with Stockdale Consulting, Inc., SRK Consulting, Inc., Benchmark Engineers, and Greystone, Pine Bluffs Lance/Fox Hills well level II study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Lance Formation Fox Hills Sandstone	Level II study designed to complete wells into the formations and evaluate aquifer characteristics and water quality.	Target flow was reached for all wells with 96% recharge. Water quality was acceptable, but has high sodium, TDS, and pH	Secure funding for and proceed with the Level III study.
JR Engineering, LLC., 2005, Cheyenne Belvoir Ranch level II study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Ogallala aquifer	Determine water sources for further development in the Ogallala aquifer in the Belvoir Ranch area	Data from 7 test wells was used to create cross sections and detailed understanding of the aquifer within the ranch. Wells 1-4 have sufficient saturated thickness; wells 6 and 9 did not meet minimum criteria. Wells are capable of 750-100 gpm pumping rates. Water meets water quality standards locally and nationally.	Monitor test wells and recommendation for drilling more.
Weston Engineering, Inc., 2005, in association with Civil Engineering Professionals, Inc., Glenrock level II well and tank feasibility study, interim report: prepared for the Wyoming Water Development Commission, variously paged. Weston Engineering, Inc., 2006, in association with Civil	Converse County	Chugwater Formation Goose Egg Formation Casper Formation Madison Limestone Flathead Sandstone	Investigate any potential impacts to groundwater and surface water sources attributed to pumping from the water supply wells near the town of Glenrock.	No discernible impact was observed at any of the monitoring stations as a result of pumping.	Maximum pump rates of 2,000 gpm. Recommended that all monitoring equipment be removed.

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Engineering Professionals, Inc., Glenrock well and tank project level II feasibility study, water tank and pipeline improvements, interim report: prepared for the Wyoming Water Development Commission, variously paged. Weston Engineering, Inc., 2007, in association with Civil Engineering Professionals, Inc., Glenrock level II well and tank feasibility study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Chugwater Formation Goose Egg Formation Casper Formation Madison Limestone Flathead Sandstone	Investigate hydrogeology of Glenrock area to determine feasibility of finding a redundant municipal water supply.	Glenrock Test Well No. was completed in the Paleozoic aquifer to a total depth of 1,233 feet below ground surface. The well can provide up to 1500 gpm of good quality water. Glenrock should purchase Glenrock Test Well No. 7 from WWDC and design and construct the necessary water delivery infrastructure to integrate the well into the town's public water system.	
TriHydro Corporation, 2006a, in association with Lidstone and Associates, Harvey Economics, and Water Rights Services, LLC., Platte River Basin plan, final report: prepared for the Wyoming Water Development Commission, variously paged.	Platte River Basin	Quaternary Tertiary Mesozoic Paleozoic Precambrian	Investigation into the available groundwater resources in the Platte River Basin, Final Report and Technical memorandums.	Summary of water use and availability and future demands for the Platte River Basin. Currently Used aquifer systems are listed.	N/A
WWC Engineering, 2006a, in association with Camp Creek Engineering, Inc., Burns and McDonnell, Wyoming Groundwater, LLC., and Fassett Consulting, LLC., Laramie water management plan level II, volume I of II: prepared for the Wyoming Water Development Commission and the City of Laramie, variously paged.	Albany County	Casper aquifer	Level II Water System Master plan to address the comprehensive water system needs for the city of Laramie.	Installation of three additional wells with a capacity of 500 gpm	The city should proceed with a Level II study including test well work.
Hinckley Consulting, 2007, in association with PMPC Civil Engineers, TST Inc., and Wester-Wetstein and Associates, Saratoga test well level II study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation	Preliminary investigation of viable groundwater source to provide sufficient quantities and quality within a 3 mile radius of the town of Saratoga.	The aquifer was found to be within drinking water standards, general behavior was that of an unconfined aquifer with transmissivity of 30,000 gpd/ft and storage coefficient of ~0.05.	Completion of permitting and design work.
JR Engineering, LLC., 2007b, Cheyenne Belvoir Ranch level II study, phase III-V, final report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	High Plains aquifer Ogallala Formation White River Formation	Characterize the present development of the groundwater resources on and around the Cheyenne Belvoir Ranch and determine the potential for future development of water resources. Summary of the Phase III-V of the Level II report.	Recommendation of completion of Test well #5 for municipal water supply. Wells should be drilled into the White River Formation to explore for future water needs.	Use of existing data for exploration of the High Plains and Casper aquifers.
JR Engineering, LLC., 2007a, Belvoir Wells No. 5 and 6 pumping test report, aquifer impact report: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Ogallala aquifer	Report describes the construction and testing of the No. 5 and 6 wells and test holes on the Belvoir Ranch.	Distinct layers of permeability have been identified within the aquifer. Both wells are hydraulically disconnected from the lower portion of the aquifer. The predicted 25 year drawdown in not considered to be significant based on a 550 and 300 gpm pumping rate.	Recommended that the water should be produced from the lower portions of the aquifer as it is disconnected with any potential surface water sources. All current monitoring stations should be continued indefinitely.

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Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
PMPC. 2007, in association with Hinckley Consulting, Encampment Sierra Madre Well level II study, summary report: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., variously paged.	Carbon County	North Park Formation	Level II study for the Encampment Sierra Madre well. The study is to investigate the possibility of supplying the town with groundwater.	Water produced is in excess of the current needs, quality is within EPA standards, no evidence for long-term decline in aquifer water levels.	N/A
Trihydro Corporation, 2007b, Project report task 1 through 6 – North Platte River groundwater assessment study southeast Wyoming (revised): Prepared for the Wyoming Water Development Commission, Cheyenne, Wy., 296 p.	Platte River Basin	Ogallala Formation Arikaree Formation Split Rock Formation White River Formation	Investigation into the available groundwater resources of the North Platte River Basin and adjacent areas of Wyoming. Tasks 1-6.	Top three prospects are the Split Rock, Hartville, and Shirley Mountains. Development of multiple prospects is recommended. Top three prospects may yield over 10,000 acre-feet per year. Based on field investigations the Hartville prospect was not recommended for development.	N/A
WWC Engineering, Inc., and others, 2007a, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., v. 1 and 2, variously paged.	State Wide	All	Wyoming Framework Water Plan, volumes I and II.	Total use of groundwater state wide totals 216,000 acre-feet per year.	N/A
AVI, 2008, in association with Black & Veatch, Dahlgren Consulting, Inc., Short Elliott Hendrickson, Inc., and Stockdale Consulting, Cheyenne/Laramie County water service area level II study volume I, Archer special use district water master plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., variously paged AVI, 2008, in association with Black & Veatch and Short Elliott Hendrickson, Inc., Cheyenne/Laramie County water service area level II study volume II, East Cheyenne water master plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., variously paged.	Laramie County	High Plains aquifer	Address water supply options and the framework for transmission of the projected development in East Cheyenne area.	Aquifers are capable of supplying sufficient quantities of water to meet projected demand.	Investigate feasibility of alternative to meet projected demands.
Olsson Associates, 2008, Manville Source Water Supply Study Level II Study, Final Report: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., 387 p.	Niobrara County	Arikaree Formation	Investigating options to bring the Manville water supply into compliance with the EPA standards for uranium.	A well field one mile north of town would eliminate the uranium contamination problems. Combining water from the new well field with the current would increase supply and decrease uranium concentrations.	Chose the lowest cost alternative, which was to install POU/POE systems.
TriHydro Corporation, 2008a, Hydrologic connection report Split Rock groundwater development project: prepared for the Wyoming Water Development Commission, variously paged. .	Natrona County	Kortes aquifer Moonstone aquifer Split Rock aquifer	Construction of two deep test wells and one test production well to fully evaluate the Split Rock prospect for ground water utilization.	The Spltirock aquifer is a closed aquifer with an average transmissivity of 48,000 gpd/ft, storativity of 0.0001, and specific capacity of 11 gpm/ft respectively.	N/A

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Weston Engineering, Inc., 2008, Douglas ground water level II study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Converse County	Casper Formation	A Level II Feasibility study for the Water System master Plan to evaluate and provide recommendations concerning the town of Douglas's water supply.	Evaluation of existing facilities results in replacement of certain portions of the current facilities.	N/A
Hinckley Consulting, 2009, in association with Wyoming Groundwater, Lusk area groundwater level I study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Niobrara County	Arikaree Formation	Collect necessary hydrologic data to determine if a Groundwater Control Area should be established.	Groundwater supply within the aquifer is sustainable at the current rate of use. Increased rate of pumping could create drawdown that is unsustainable.	Acquire necessary permits to produce groundwater from the aquifer.
JR Engineering, 2009, Laramie County Aquifer Study, Final Report, 110 p.	Laramie County	High Plains aquifer	Laramie County aquifer Study to determine the hydrologic state of the High Plains aquifer within Laramie County.	There are currently over 12,000 permits issued for wells in the county. All precipitation is a source of recharge for the aquifer. Projected water use ranges from 5,299-10,066 acre feet per year with 25-42 actively pumping wells.	N/A
JR Engineering, 2009, in association with Lidstone and associates, Inc., Master plan level I study for the Town of Pine Bluffs, WY: prepared for the Wyoming Water Development Commission, variously paged.	Laramie County	Brule aquifer Lance aquifer	Level I study to review the existing system and present system upgrades for the town of Pine Bluffs.	Wells into the Lance aquifer were constructed in order to create a consistent supply source in conjunction with inconsistent Brule aquifer after a 20 foot decline and dewatering in some locations.	Proceed with Level II study
TriHydro Corporation, 2009, Belvoir Ranch High Plains aquifer—White River study, project report: prepared for the City of Cheyenne, Board of Public Utilities, and the Wyoming Water Development Commission, variously paged.	Laramie County	White River Formation	Groundwater production potential from the White River Formation in the vicinity of the Belvoir Ranch.	The data collected during the survey suggests that the White River Formation in this vicinity will not yield sufficient water for use as a municipal supply for the city of Cheyenne.	N/A
Wyoming Groundwater, LLC, 2009, in association with WWC Engineering, Glendo water supply level II study: prepared for the Wyoming Water Development Commission and the Town of Glendo, variously paged.	Platte County	Quaternary Alluvium Arikaree Formation White River Formation Permian-Triassic Red Bed Sequence Hartville Formation	Glendo Water Supply Level II Study to define water supply capabilities and demand, identify water supply improvement options, perform well siting studies, construct and evaluate a test well, and provide conceptual designs for proposed system improvements.	The current supply capacity complies with WDEQ regulations; however it does not comply with future demand increases. Pilot Hole # 5 is the most favorable site for a new municipal well with test results of 200 gpm of good quality water. Recommendations include purchasing well at Pilot Hole # 5 from WWDC and installing a pressure transducer to define water level fluctuations.	N/A
DOWL HKM, 2010, in association with Weston Engineering, Inc. and CEPI, Douglas master plan level I study, final report: prepared for the Wyoming Water Development Commission and the City of Douglas, variously paged.	Converse County	Ogallala Formation through Fremont Canyon Sandstone	Douglas Master Plan Level I Study to evaluate the existing water system, and recommend improvements to the system. Some improvements may require studies outside the scope of this Level I study.	City should begin planning for additional supply as it is only slightly greater than current peak day use. Possible developable groundwater supplies were identified that would meet short-term and long-term needs.	It is recommended that a request for Level III funding be made for replacement and rehabilitation of existing facilities.

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Jehn Water Consultants, Inc., 2010, in association with Tetra Tech, Laramie water management study level II phase II, final report, prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Casper aquifer	As part of the previous Level II, Phase II project completed by Tetra Tech in May of 2010, an Aquifer Storage and Recovery (ASR) test was done on the Spur well field. This report examines the possibility of storing water in the Casper aquifer for use during peak demands as part of the ASR test.	Water injected into the aquifer through an injection well during four steps increased the water level in the Spur Well No. 1 approximately 30 m away, 2.3 feet. Eight days after the testing the water level remained 0.79 feet higher than the prior static water level. Water quality was virtually unchanged by the process. It is recommended that production wells be drilled that penetrate all five members of the Casper aquifer.	N/A
Tetra Tech, 2010, Laramie water management phase II level II water system report, final report: prepared for the Wyoming Water Development Commission, variously paged.	Albany County	Casper aquifer	Phase II, Level II Water System Report for the city of Laramie. Scope of study includes: GIS work, hydraulic modeling, aquifer storage and recovery study, and long-term groundwater treatment of the Casper aquifer.	The existing hydraulic water model of the city's distribution system was updated and calibrated, required more work than initially planned, therefore elements of the original scope of work were abandoned. It is recommended that the South Laramie Connection be designed.	N/A
Wester Wetstein & Associates, 2010, in association with James Gores & Associates and Olsson Associates, City of Rawlins water master plan level I, final report: prepared for the Wyoming Water Development Commission and the City of Rawlins, variously paged.	Carbon County	Nugget Formation	Rawlins Water Master Plan Level I provides a working model of the distribution system and examines the adequacy of the existing supplies to meet projected needs.	Overall the water system was found to be in great condition, however many improvements are needed and include the replacement of the pipeline between the Water Treatment Plant Pipeline and Atlantic Rim Reservoir, and establishing a program of usage for the Nugget wells.	WWDC has begun the process of appropriating funds for the new pipeline.
Wester Wetstein & Associates, 2010, in association with James Gores & Associates and Olsson Associates, Town of Wheatland master plan level I study, final report: prepared for the Wyoming Water Development Commission and the Town of Wheatland, variously paged.	Platte County	Arikaree Formation	Wheatland Master Plan Level I Study gives an overview of the town's water system by identifying areas of improvement, and provides a planning horizon for the next 30 years.	The current supply is sufficient for future demand. System is operated very effectively with no need of any major modifications. Some of the pumps in the booster stations appear to have substantial wear. It is recommended that pump inspections be performed to check their condition.	N/A
Lytle Water Solutions, LLC, 2011, Managed aquifer recharge, storage and recovery project, final report, prepared for the Wyoming Water Development Commission and the Cheyenne Board of Public Utilities, variously paged.	Laramie County	Ogallala aquifer White River aquifer Casper Formation	A multi-phase investigation of the feasibility and benefits of aquifer storage and recovery (ASR) technologies on applicable well fields near Cheyenne.	The Ogallala aquifer is experiencing water level declines that may be related to a number of factors. There will most likely be years with excess water, so a full-scale recharge operation is favorable.	N/A

Appendix B WWDC Groundwater Studies

Citation(s)	Location	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
PMPC, 2011, in association with Hinckley Consulting, Groundwater exploration program Riverside No. 7 Well, Sierra Madre Water and Sewer Joint Powers Board: prepared for the Wyoming Water Development Commission, variously paged.	Carbon County	North Park Formation	Groundwater Exploration Program for Town of Riverside No. 7 Well. Goal is to complete and test an additional water-supply well.		N/A
WWC Engineering, 2011, in association with Wyoming Groundwater, Lance Creek water supply study level I: prepared for the Wyoming Water Development Commission, variously paged.	Niobrara County	Inyan Kara Group	Level I water Supply Study for the Town of Lance Creek, Examine the town's public water system and current groundwater wells	Recommend Level II Study (in progress) and installation of test wells to find new source water for town.	Groundwater study in progress.

Appendix C

GIS Dataset Sources for Figures and Plates

James Stafford and Tomas Gracias

Appendix C - GIS Dataset Sources for Plates and Figures

Dataset	Presented in	Original Source
GEOLOGY		
Platte River Basin faults	Plate I	Stoeser, D.B., et al., 2005
Precambrian basement structure	Plate I	Blackstone, 1993
Precambrian basement faults	Plate I	Blackstone, 1993
Lineaments	Plate I	Cooley, 1986
Bedrock Geology	Plate I, Plate II	USGS, 2005
Hydrogeology	Plate II	Bartos, T.T., 2012
Cross section lines	Plate I	See GEOLOGIC CROSS SECTIONS
WSGS Regions	Figure 3-1, various figures Chapter 8	WSGS/USGS, 2012
GEOLOGIC CROSS SECTIONS		
Geologic cross section A-A'	Figure 4-2. Geologic cross section A-A'	Love, 1965
Geologic cross section B-B'-B"	Figure 4-3. Geologic cross section B-B'-B"	Trihydro, 2008
Geologic cross section C-C'	Figure 4-4. Geologic cross section C-C'	Blackstone, Jr., D.L., 1993
Geologic cross section D-D'	Figure 4-5. Geologic cross section D-D'	Cserna, E.G.; Kerns, G.J.; Laraway, W.H., 1983
Geologic cross section E-E'	Figure 4-6. Geologic cross section E-E'	Harshman E.N., 1968
Geologic cross section F-F'	Figure 4-7. Geologic cross section F-F'	Blackstone, Jr., D.L., 1993
Geologic cross section G-G'	Figure 4-8. Geologic cross section G-G'	Blackstone, Jr., D.L. , 1970
Geologic cross section H-H'	Figure 4-9. Geologic cross section H-H'	Blackstone, Jr., D.L., 1970
Geologic cross section I-I'	Figure 4-10. Geologic cross section I-I'	Blackstone, Jr., D.L., 1969
Geologic cross section J-J'	Figure 4-11. Geologic cross section J-J'	Ver Ploeg, A.J., 2007
Geologic cross section K-K'	Figure 4-12. Geologic cross section K-K'	Ver Ploeg, A.J. and McLaughlin, F.J., 2009
Geologic cross section L-L'	Figure 4-13. Geologic cross section L-L'	Ver Ploeg, A.J., 2009
Geologic cross section M-M'	Figure 4-14. Geologic cross section M-M'	Ver Ploeg, A.J., 2007
Geologic cross section N-N'	Figure 4-15. Geologic cross section N-N'	Blackstone, Jr., D.L., 1996
Geologic cross section O-O'	Figure 4-16. Geologic cross section O-O'	Blackstone, Jr., D.L., 1996
Geologic cross section P-P'	Figure 4-17. Geologic cross section P-P'	McLaughlin, J.F.; Stafford, J.E; Harris, R.E, 2011
Geologic cross section Q-Q'	Figure 4-18. Geologic cross section Q-Q'	Harris, R.E.; McLaughlin, J.F.; Jones, R.W., 2006

Geologic cross section R-R'	Figure 4-19. Geologic cross section R-R'	Harris, R.E.; McLaughlin, J.F.; Jones, R.W., 2005
Geologic cross section S-S'	Figure 4-20. Geologic cross section S-S'	Blackstone, Jr., D.L., 1996
GROUNDWATER		
Anomalous geothermal gradients	Figure 4-21.	Hinckley and Heasler, 1984 Buelow, 1986
Aquifer recharge as a percent of precipitation	Figure 5-2.	Hamerlinck and Arneson, 1998
Aquifer sensitivity	Figure 5-3.	Hamerlinck and Arneson, 1998
Average annual precipitation, 1981-2010	Figure 3-3.	PRISM Climate Group, 2012
Colorado groundwater well permit	Ch.8 Figures	Colorado Division of Water Resources
Environmental water sample locations	Figure 7-1.	USGS, Environmental water sample locations GIS dataset of 2010
Estimated net annual aquifer recharge	Figure 5-2.	Hamerlinck and Arneson, 1998
Green Areas	Figure 9-1.	Hinckley, 2006
Groundwater Control Areas	Figure 9-1.	Wyoming State Engineer's Office, 2012
Nebraska groundwater well permit	Ch.8 Figures	Nebraska Department of Natural Resources
Produced water sample locations	Figure 7-1.	USGS, Wyoming Water Science Center, 2010
Springs	Figure 8-34.	Stafford and Gracias, 2009
SWAP locations	Figure 8-23.	Trihydro Corporation, 2004
North Platte Groundwater Assessment Targets	Figure 9-1.	Trihydro, 2004
Groundwater Development Potential for the Paleozoic Aquifer SE Wyoming	Figure 9-1.	Western Water Consultant's Inc, 1982
Platte/Goshen Regional Water Plan Groundwater Prospects	Figure 9-1.	Trihydro, 2004
WSEO groundwater permits	Ch.8 Figures	Wyoming State Engineer's Office, e-Permit database of 2011
POTENTIAL GROUNDWATER CONTAMINANTS		
Abandoned mine sites	Figure 5-7.	WDEQ Abandoned Mine Land table of 2010
Active coal mine	Figure 5-8.	WDEQ, 2011
Active injector and disposal wells associated with oil and gas	Figure 5-4.	WOGCC well header data as of 2011
Active large mine permits	Figure 5-8.	WDEQ Land Quality Division (LQD) large and small active mine permit tables of 2010

Active small mine permits	Figure 5-8.	WDEQ Land Quality Division (LQD) large and small active mine permit tables of 2010
Active limited mine operations (ETs)	Figure 5-8.	WDEQ LQD limited mine operation GIS dataset of 2009
Active storage tanks	Figure 5-10.	WDEQ Solid and Hazardous Waste Division (SHWD), 2011
Active Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Figure 5-5.	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2009
Expired Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Figure 5-5.	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2009
Concentrated Animal Feeding Operations (CAFOs)	Figure 5-6.	WDEQ/WQD CAFO table of 2009
Known contaminated groundwater areas	Figure 5-10.	WDEQ/WQD Groundwater Program known contaminated areas GIS dataset of 2009
Oil and gas fields (polygons)	Figure 5-4.	De Bruin, 2007
Oil and gas fields (points)	Figure 5-4.	De Bruin, 2007
Orphan sites	Figure 5-10.	WDEQ SHWD orphan site GIS dataset of 2009
Permanently abandoned injector and disposal wells associated with oil and gas	Figure 5-4.	WOGCC well header data as of 2011
Pipelines (not for distribution)	Figure 5-4.	Wyoming Pipeline Authority pipeline GIS dataset of 2007
Refineries	Figure 5-4.	WSGS/WOGCC
Solid and hazardous waste facilities	Figure 5-6.	WDEQ SHWD solid and hazardous waste facilities table of 2009
Underground Injection Control (UIC) Class I and V wells	Figure 5-5.	WDEQ/WQD UIC GIS dataset of 2011
Voluntary Remediation Program (VRP) sites	Figure 5-10.	WDEQ SHWD VRP tables and GIS datasets of 2010
WSGS mines, pits, mills, and plants	Figure 5-. 9	Harris, 2004
BASE DATA		
Basin boundaries	Plate I, Various figures	U.S. Department of Agriculture, 2002
Hillshade	Various figures	U.S. Geological Survey, 1999
Elevation	Various figures	U.S. Geological Survey, 1999
Lakes	Plate I, Various figures	
Rivers	Plate I, Various figures	
Wyoming, Colorado, and Montana towns	Plate I, Various figures	National Atlas of the United States, 2004

Appendix D

Criteria for Hydrologic Connection

Bern Hinckley

HINCKLEY
CONSULTING
P.O. Box 452 Laramie, WY 82073 307-745-0066 bhinckley@aol.com

MEMORANDUM

TO: Matt Hoobler DATE: February 7, 2011

FROM: Bern Hinckley PROJECT: North Platte Technical Support

SUBJECT: Hydrological Connection

This memo has been prepared at the request of the Wyoming State Engineer's Office (SEO) to provide background and screening criteria for assessment of "hydrological connection" of groundwater wells in the North Platte River Basin under the provisions of the Modified North Platte Decree and the Platte River Recovery Implementation Program (PRRIP), i.e. the "28:40" connection criteria. Following discussion of the origin and associated principles, a step-by-step approach to application is suggested. The final section provides references and calculation tools.

BACKGROUND / HISTORY

MBSA, 1982. For a series of reports published in 1982, the Missouri Basin States Association developed an analysis of the impact of groundwater development on streamflow, i.e. "stream depletion", for the Platte and Kansas Rivers and their major tributaries, including the North Platte River (MBSA, 1982). This work developed a series of maps which included lines of equal hydrological connection for groundwater wells along the studied rivers, i.e. all wells along a given line would have the same depletive effect on the stream, as a proportion (percentage) of their groundwater pumping.

These maps were based on the concept of a "stream depletion factor" (sdf), as developed by Jenkins (1968). In an ideal aquifer/stream system (Figure 1) the rate of stream depletion can be estimated as a function of:

a = distance from the well to the stream (ft.);
S = specific yield of the intervening aquifer (dimensionless); and
T = the transmissivity of the intervening aquifer (ft^2/day).

using mathematical relationships published by Glover and Balmer (1954). Jenkins combined these factors into a single term, "sdf", and provided tables and graphs relating sdf with stream depletion rates and volumes to simplify the calculations and to facilitate calculations for complex pumping patterns (like seasonal irrigation).

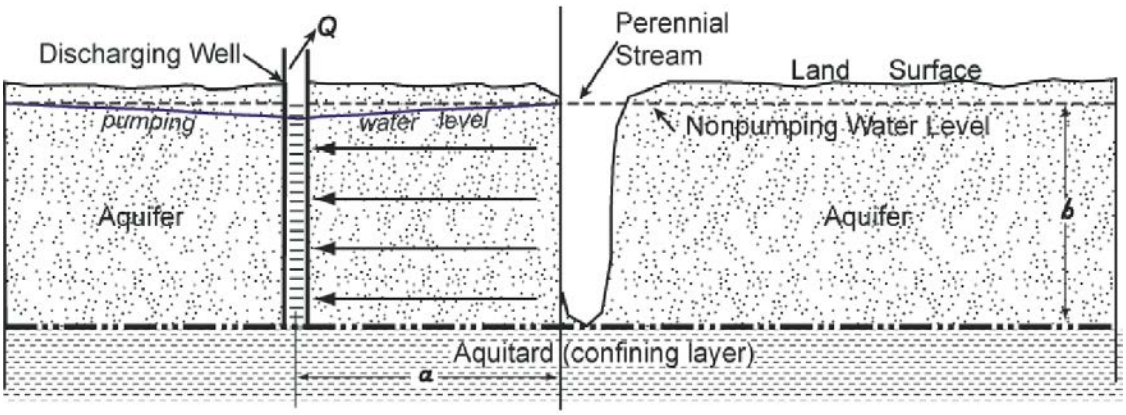

Figure 1 - Idealized "Glover" Model

In the idealized system of Figure 1:

$$sdf = a^2S/T$$

For non-ideal systems, Jenkins proposed an "effective value" of sdf be determined which incorporates, for example, "irregular impermeable boundaries, stream meanders, aquifer properties and their areal variation, distance from the stream, and imperfect hydraulic connection between the stream and aquifer." (Jenkins, 1968; p. 2). For the MBSA (1982) study, which was primarily concerned with stream depletion through groundwater development of the limited-width alluvial aquifers along major streams, sdf values were determined through numerical groundwater modeling of representative stream reaches.

The units of sdf are days. "When the well is pumped continuously and when the volume of depletion reaches 28 percent of the total volume pumped, the pumping time would be approximately equal to one sdf at the well." (MBSA, 1982; p. 9). For example, at a point in the aquifer where the combination of local transmissivity, specific yield, and distance create an sdf value of 500 days, the cumulative stream depletion after 500 days of pumping will be 28%. The cumulative depletion will be less than 28% at 400 days and more than 28% at 600 days. 28% is simply the cumulative depletion at the point in time where the pumping time is numerically equal to the sdf value.

Available data on specific yield and transmissivity were compiled for the aquifers along the streams of interest and the points at which the cumulative stream depletion equaled 28% of the volume pumped at specified times were calculated. These points defined a series of "sdf lines", which were extended loosely parallel to the studied streams -- greater sdf values at greater distance from the stream, smaller sdf values at smaller distances from the stream. Five sdf bands were developed and plotted on these maps, for sdf = 50, 500, 1500, 5,000, and 15,000 days.

15,000 days is approximately 40 years, which was the planning horizon adopted for the overall study program (1944 - 1983). Thus, the cumulative depletion from a point on the outermost mapped line (sdf = 15,000 days), after 40 years of continuous pumping, would be 28%.

The MBSA (1982) study then estimated pumping volumes from irrigations wells within each sdf band (between two sdf lines) and used the sdf bands to calculate the resulting streamflow depletions. Rather than extending explicit calculations to irrigation wells beyond the 15,000-day (40-year) band, all wells outside this line were simply assumed to have an aggregate instantaneous depletive impact of 2% of the amount pumped[1].

Modified North Platte Decree. As streamflow depletion by groundwater irrigation developed as an issue in the 1986 - 2001 Nebraska v. Wyoming lawsuit over the flows of the North Platte River (U.S. Supreme Court No. 108, Orig.), the parties' experts sought to quantify the impact on streamflows of irrigation well development over the period since the original (1945) North Platte Decree. Eventually, the settlement negotiations that resolved the lawsuit, resulting in the 2001 Modified North Platte Decree, boiled the groundwater-irrigation issue down to an assessment of which tracts of groundwater irrigation would be accounted under the agreed-upon limitations on total irrigated acreage and total consumptive use of irrigation water in various sub-basins of the North Platte River in Wyoming. For the North Platte River basin above Guernsey Dam both irrigated acreage and consumptive use limits were established; for the lower Laramie River basin (east of the Laramie Mountains) exclusive of the Wheatland Irrigation District, only an irrigated acreage limitation was established. As a negotiated criteria for identification of which irrigated areas would "count" and which would not, the parties adopted a concept of "hydrological connection" based on the location of the groundwater irrigation supply well:

> "A hydrologically connected groundwater well is one that is so located and constructed that if water were intentionally withdrawn by the well continuously for 40 years, the cumulative stream depletion would be greater than or equal to 28% of the total groundwater withdrawn from the well." (North Platte Decree Committee Charter - Exhibit 4, Sec. III, D, 2, b.)

For an initial definition of irrigation wells for which the associated irrigated acreage would be accounted under the Modified Decree, maps were developed by Wyoming and approved by the North Platte Decree Committee (NPDC) based on the best available hydrogeologic information. (No new aquifer data were developed for that analysis.) In some cases, e.g. the lower Laramie River basin, the delineation of "hydrological connection" under the 28:40 criteria was based on existing numerical modeling (i.e. MODFLOW). In most cases, the simpler, stream-depletion

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[1]No details are provided on the origin of the 2% estimate; the authors "recommend that criteria for areas outside the study limits of the SDF technique be developed and used in the next study."

factor approach (Jenkins, 1968), with sdf $= a^2S/T$, was used[2]. The areas on these maps outside the 28:40 areas, shown in green, i.e. those areas judged not to be "hydrologically connected" under the 28:40 criteria, have come to be known as the "green areas", in the sense of a "green light" with respect to Decree restrictions on groundwater use.

Because the streamflows of interest were those entering Nebraska from Wyoming's North Platte River Basin, the stream impacts of concern are those contributing to (or subtracting from) flows at the stateline. Depletions to certain streams, which do not directly contribute to flows at the stateline, do not fall under the Modified Decree "hydrological connection" criteria. As per the procedures adopted by the NPDC, qualifying depletions are those to "perennial streams" which flow through to the mainstem of the North Platte River, as defined by the standard 1:100,000-scale topographic maps produced by the U.S. Geological Survey.

In Wyoming, there are many ephemeral streams which, when they flow at all, are essentially perched above the local groundwater table. These streams lose streamflow to groundwater, but the rate of loss is not affected by the elevation of the underlying groundwater table. A lowering of the groundwater table through pumping does not affect the rate of streamflow loss. No "depletion" occurs as a result of groundwater pumping under these circumstances.

Streams in the mountains of Wyoming are commonly perennial, gain water through groundwater inflow, and can be depleted through groundwater pumping. However, many of these streams become ephemeral once they exit the mountains, losing all perennial flow to the underlying aquifers (e.g. an alluvial fan at the mouth of a stream canyon). Because a depletion to such a stream is not directly translated through to the mainstem of the North Platte River and thus to the stateline, no "depletion" is considered to occur under the Modified Decree. (A more complex analysis is needed in areas where a depleted perennial stream becomes ephemeral close enough to a mainstem tributary that a 28% depletion may occur via the remaining, groundwater connection in less than 40 years.)

Included with adoption of the criteria defined for hydrological connection and the initial hydrological connection maps, was recognition that the maps approved by the NPDC were deliberately conservative, intended to err on the side of smaller rather than larger "green" areas. Because many areas which had <u>not</u> been identified as "green" might still have depletions of less than 28% in 40 years, the NPDC procedures allow case-by-case application of the criteria based on local data and more detailed studies. For example, the hydrological connection between a stream and a nearby well developing groundwater from a deep, confined aquifer might be quite small despite the fact that, in map view, the well is relatively close to the stream.

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[2]In the absence of a more complicated determination of an effective sdf value, Jenkins (1968) is essentially reduced to the configuration of Figure 1 and the equations of Glover and Balmer (1954). Narrow, high-transmissivity alluvial aquifers are largely ignored as being clearly within the bounds of "hydrological connection". (See individual map descriptions for details.)

As of this writing, Modified Decree compliance with respect to annual irrigated acreage and consumptive use accounting associated with hydrologically-connected groundwater is based on the NPDC "green area" maps and a small number of individual site studies that have applied the 28:40 criteria outside the previously defined areas.

Platte River Recovery Implementation Program (PRRIP). Similar issues regarding the impact of groundwater development on streamflow were subsequently resolved in the development of the Platte River Recovery Implementation Program (PRRIP). Recognizing that beyond a certain degree of hydrological connection, the estimation and accounting of groundwater impacts fell below an appropriate level of concern, the parties to that program negotiated adoption of the 28:40 hydrological connection criteria from the Modified North Platte Decree. With the same provisions for future individual studies, hydrological-connection maps as described above were developed for the remaining portions of the North Platte River basin in Wyoming (North Platte River below Guernsey Dam and upper Laramie River basin) and it was agreed that groundwater development outside the 28:40 bounds would be exempt from the recovery program.

As of this writing, PRRIP compliance with respect to 1997 "baselines" and calculation of "new" depletions are based on the "green area" maps in the Wyoming Depletion Plan and a small number of individual site studies that have applied the 28:40 criteria outside the previously defined areas.

The SEO website (http://seo.state.wy.us/) provides electronic versions of the "green area" maps for the various North Platte River sub-basins, and related policy documents.

PRINCIPLES

In principle, nearly all sources of groundwater are connected to surface water resources to some degree. Exceptions include connate water (e.g. sea water remaining since the original deposition of a formation) and, sometimes, water associated with hydrocarbon deposits. For the most part, groundwater of sufficiently high quality to be of value for irrigation, domestic, municipal, and stock use is likely to be part of an active groundwater flow system that, however slowly, begins and ends at the earth's surface.

The basic, physical constraint of "mass balance" requires that any increase in groundwater consumption at one point must be balanced by an equal decrease in storage or consumption somewhere else. For groundwater systems in which the hydrological connection with surface water is small, most of the extracted groundwater comes from storage within the aquifer. This is reflected in a decrease in aquifer water level or pressure (head). For groundwater systems in which the hydrological connection with surface water is large, most of the groundwater comes from surface depletions, and there may be little change in aquifer water levels. A third possible "source" of groundwater is a decrease in withdrawals elsewhere. For example, the term "ET salvage" is applied where the consumption of water by non-beneficial vegetation or natural evaporation is reduced as groundwater is withdrawn for crop consumption, with no decrease in

streamflow or in aquifer storage (beyond the initial water-level drop that dries up the impacted evapotranspiration).

Thus, "hydrological connection" is rarely a binary, "connected" vs. "not connected" assessment. Instead, the reasonable working hypothesis is that aquifer and stream are connected, and one seeks to estimate or measure the degree of connection, commonly with reference to some regulatory, negotiated, or policy standard criteria. The 28:40 criteria presented in the Modified North Platte Decree for accounting and compliance with limitations on irrigated acreage and the consumptive use of irrigation water is an example of such a standard. That same standard was adopted by the parties to the PRRIP for their accounting and replacement water calculation procedures.

Other programs and jurisdictions have adopted different standards, for different purposes. In Colorado, for example, groundwater development that is calculated to have a 0.1% depletive effect in 100 years is considered "tributary" to surface water. The 2004 Platte River Conjunctive Management Study in Nebraska stated, "Hydrologic connection exists where pumping will cause a streamflow depletion within 50 years greater than 10% of the pumping rate." The latter example also differs from the 28:40 criteria in that it specifies a rate of depletion, rather than being based on the cumulative volume of depletion. (Under steady pumping, the rate of depletion, e.g. in gpm, will always be higher as a percentage of the pumping than the cumulative volume of depletion will be, because small depletion rates early in the pumping period will average out the higher depletion rates of later in the pumping period.)

The hydrological connection criteria cited above, including the 28:40, are all based on proportions rather than absolute volumes. For example, a stream depletion of 50 ac-ft would not be considered "connected" under the 28:40 criteria if the cumulative volume pumped over 40 years were more than 200 ac-ft (i.e. a 25% depletion), whereas a stream depletion of 5 ac-ft would be considered "connected" if the cumulative volume pumped were less than 17 ac-ft (i.e. a 29% depletion). High-yield wells are neither more nor less likely to be meet the criteria for hydrological connection than low-yield wells; nor is there any production threshold below which depletion is automatically considered inconsequential.

Beyond the consideration of groundwater impact with respect to whether a stream is perennial or not (discussed above), a proportion-based criteria for hydrological connection like the 28:40 is inherently insensitive to the flow rate of the stream. This creates an algebraic breakdown for particularly small streams, in that a 1000 gpm well cannot possibly exceed a depletion rate of 10% if the impacted stream only flows 100 gpm in the first place, regardless of distance, transmissivity, time, etc. To date, this issue has not been addressed with respect to application of the Modified Decree and PRRIP "hydrological connection" criteria.

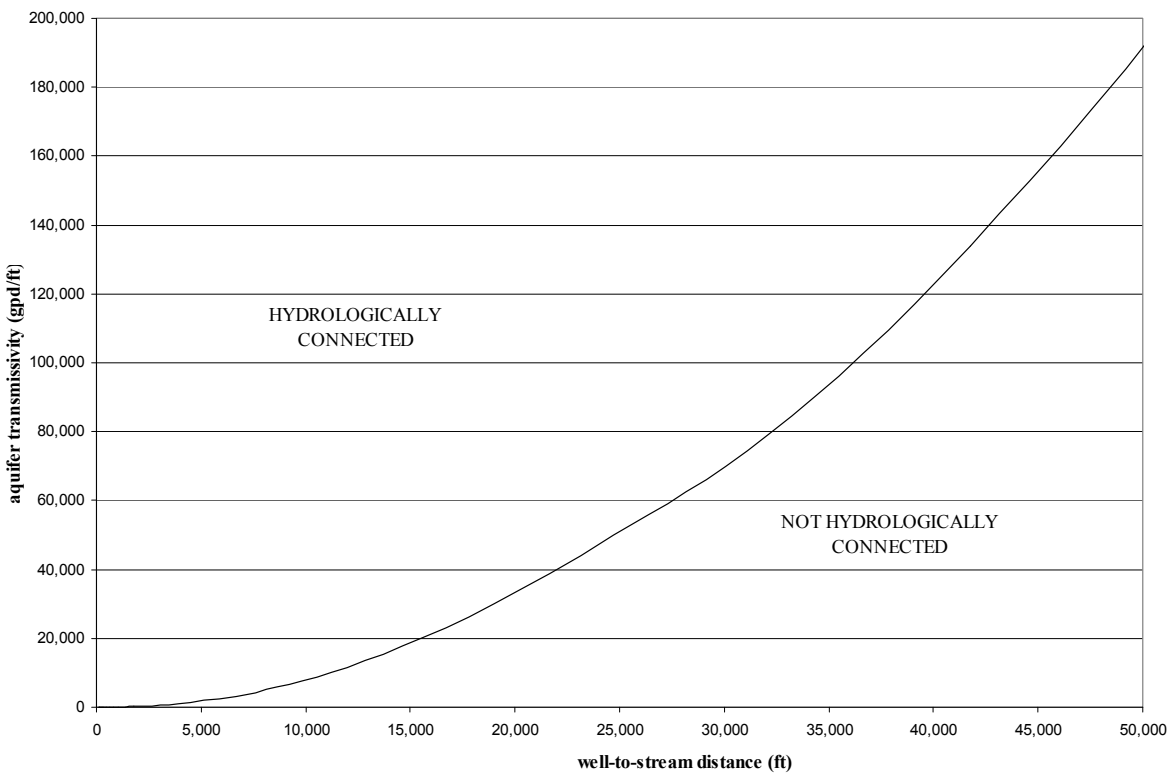
Hydrological connection is calculated under the 28:40 criteria without regard to the flow direction of groundwater. Stream depletion resulting from water physically leaving the stream to enter the aquifer being pumped is treated the same as stream depletion resulting from pumping

groundwater that would otherwise flow on into the stream. This reflects the hydrologic principle of "superposition" which recognizes that the impact of a pumping well is simply added to whatever other stresses, gradients, impacts, etc. are otherwise present.

APPLICATION

Figure 2 presents the 28:40 criteria for hydrological connection as calculated for an ideal (i.e. thick, homogeneous, isotropic, "sandbox") aquifer. The figure assumes a generic, unconfined-aquifer specific yield of 0.15, then plots the line along which the transmissivity and distance parameters produce a 28% cumulative depletion in 40 years. The area above and to the left of the line represents wells for which either the distance to the stream is small enough and/or the transmissivity is high enough that the depletion is greater than 28%. Only where the distance is large enough or the transmissivity is small enough (the right-hand side of the graph), will wells in this idealized scenario be classified as "not hydrologically connected".

Figure 2 -- 28% Depletion in 40 Years (S = .15)
idealized aquifer



Consider an 8-inch diameter municipal-supply well for which the desired yield is 300 gpm. Under the idealized conditions of Figure 2, for drawdown to remain within reasonable magnitude, say 300 ft., a transmissivity in excess of 1,500 gpd/ft is required[3]. Such a well would have to be at least 4,400 ft from the stream to be considered not hydrologically connected under the 28:40 criteria. Absent contrary indications (discussed below), productive wells closer to the stream are likely be classified as "hydrologically connected" under the 28:40 criteria.

Given enough time, one might address the question of hydrological connection through direct observation, i.e. pump a well, measure flow in the potentially impacted stream, and see what happens. In practice, the 28:40 threshold for "connection" is likely too low to be directly assessed. Typical pump tests are run from a few hours to a few days. Where a critical factor in an important project cannot be adequately investigated without a longer test (e.g. delayed yield or where aquifer boundaries are expected), multi-week pump tests are occasionally justified. However, for a well in an ideal aquifer to fall outside the 28:40 criteria, the depletion rate over even a 60-day test would be less than 0.01% - almost certainly too small to be detected by direct streamflow measurements. If <u>any</u> discernable depletion were measured in a direct test, it would be clear that the well would be classified as "connected" under the 28:40 criteria, but the absence of discernable depletion could <u>not</u> be interpreted to mean the well would be classified as "not connected".

Thus, assessment of hydrological connection under a 28:40 criteria is almost inevitably based on groundwater theory (modeling), where aquifer hydrogeologic parameters are quantified and used to mathematically predict impacts over extended time periods, rather than relying on direct observation. Suitable models of aquifer behavior for predicting stream depletion impacts vary from such simple, 3-parameter equations as the "sdf" method described above (and used to develop Figure 1), to complex, multi-layer numerical models such as those built within the MODFLOW[4] structure.

Hydrogeologic Parameters

<u>Specific yield (storage coefficient; storativity)</u>. This parameter is necessary for even the simplest models, as it reflects the volume of water available for each increment of drawdown. The higher the specific yield, the more of the pumping demand that is met by release of aquifer storage and the less that is met by stream depletion. Specific yield values for the unconfined aquifers associated with surface interaction commonly fall in the range of 0.10 - 0.20. Storage coefficients derived from short-term pump tests should be evaluated with care, in that initially low, confined-aquifer values may approach unconfined-aquifer values over the extended time

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[3]The conversion between transmissivity units is: 1 ft^2/day = 7.48 gpd/ft

[4]MODFLOW is a standard, finite-difference groundwater flow model developed by the U.S. Geological Survey. There are many commercial versions of this model, for which graphical pre- and post-processors have been added to facilitate use.

periods of interest here, i.e. a 40-year view that includes "delayed yield" reactions, the spread of drawdown into unconfined portions of a locally confined aquifer, etc.

Transmissivity. This parameter is also necessary for even the simplest models, as it reflects the ease with which water moves through the aquifer, between stream and well. Higher transmissivities produce higher stream depletion, all else being equal. Typically, wells are sited to maximize transmissivity, e.g. targeting coarse-textured zones or fracture zones, whereas the wider-area of the aquifer between well and stream may have a lower effective transmissivity. Use of a transmissivity value from a singularly productive well may thus be conservative in the sense of tending to overestimate stream depletion. Similarly, because transmissivity is the product of permeability and aquifer saturated thickness, transmissivity will decrease as drawdown develops in an unconfined aquifer. Simple models of stream depletion assume an effectively constant transmissivity (i.e. that the saturated thickness does not significantly decrease with pumping), which may not be the case in relatively thin aquifers.

Hydraulic parameters for "confining" units. Based on lithologic considerations or pump-test drawdown measurements in various geologic layers , it may be possible to develop quantitative estimates of the permeability of significant low-permeability zones between the well and stream. The common mistake of a "not hydrologically connected" conclusion based simply on measurement of a head difference between two hydrogeologic units should be avoided. Head differences, whether vertical or horizontal, identify groundwater gradients and the resulting groundwater flow directions. Only combined with credible permeability information can hydrological connection interpretations be supported.

Boundaries. Pump tests of sufficient duration and/or geologic interpretation may provide aquifer boundary information. "Negative" boundaries in a pump test, e.g. when the cone of depression generated by well pumping encounters the termination of a water-bearing unit, suggest greater isolation of the aquifer from its surroundings, decreasing the opportunity for hydrological connection with the surface. "Positive" boundaries, particularly the occurrence of a point in time in a pump test beyond which no additional drawdown takes place, suggest a "recharge" source, the most likely candidate for which is commonly a surface-water feature.

In the development of parameters with which to project hydrological connection, pump-test drawdown data from observation wells can be particularly important in assessment of hydrogeologic conditions through the wider aquifer (away from the pumped wellbore) However, variation in groundwater levels near an impacted stream are strongly limited by the presence of the stream. The stream is depleted as it "works" to maintain adjacent groundwater levels. The perhaps subtle change in groundwater gradients accompanying stream depletion are necessarily less apparent close to the stream. The absence of readily discernable near-stream drawdown in the aquifer cannot be taken as demonstration that a pumped well is having little impact on streamflow.

Hydrogeologic Setting

Most of the initial "green area" maps developed for compliance and application of the Modified Decree and the PRRIP were produced by applying conservative parameters (e.g. using the highest of reasonable transmissivity values) and conservative assumptions (e.g. a continuous, homogeneous aquifer; a fully-penetrating stream) to a simple, idealized model of aquifer behavior, across large areas of the North Platte River basin. This broad approach was deemed inappropriate for geologically complex areas, e.g. much of the area south of the North Platte River between Casper and Douglas, and was recognized as ignoring many factors that, at a local scale, may serve to reduce or enhance hydrological connection. These are factors best addressed on a case-by-case basis, where detailed data collection and interpretation are available, and where site-specific groundwater modeling that takes more information into account can be developed.

In all cases, the general hydrogeologic setting of a well should be considered as part of the assessment of hydrological connection. Where the simple geometry of an aquifer makes the low magnitude of potential connection obvious, e.g. an aquifer with no outcrop within tens of miles, confined beneath several thousand feet of low-permeability shale, limited or no quantitative modeling may be necessary. In any case, the following hydrogeologic factors should be considered in assessment of the appropriate level of analysis:

Stratigraphy. Streams rarely fully penetrate the aquifer, as assumed by the simple, Glover-type models (Fig. 1) Where a well is completed in the deep zones of an aquifer while the stream penetrates only the uppermost zones, the thickness of the aquifer itself may become a significant factor in stream depletion. For this reason, even in a homogeneous aquifer, a shallow well is somewhat more likely to qualify as "connected" than a deep well.

Low-permeability formations/layers between the aquifer and the stream serve to reduce the degree of hydrological connection. Thickness is a key component, of course, in that the thicker the low-permeability layers are, the less the hydrological connection. The lateral continuity of a restricting or confining layer is also important, in that groundwater flow may "short-circuit" a low-permeability unit where the unit is thin or absent.

Geologic Structure. Most of the above discussion assumes horizontal orientations, e.g. an aquifer beneath a low-permeability layer remains separated from the surface at all locations. This conceptualization is incorrect where strata are dipping or are broken by faults or fractures.

Although the aquifer may be separated from the stream by low-permeability intervening strata at the closest point, the aquifer may be exposed to the surface and stream at an up-dip location close enough to meet hydrological connection criteria.

If an inter-formation fault juxtaposes the aquifer against a low-permeability unit between the well of interest and the potentially impacted stream, hydrological connection may be severed or

greatly inhibited. On the other hand, intra-formational faults are generally considered to greatly enhance permeability. If such faulting/fracturing provides a groundwater pathway between aquifer and stream, hydrological connection will be greatly enhanced.

In many bedrock aquifers, fracturing (e.g. associated with faulting) is the predominant source of permeability. As with the faults themselves, fracture zones may provide a high-permeability pathways between well and stream, along which hydrological connection is enhanced.

Stream/Aquifer Continuity. The setting of a "perched" stream, where a stream is hydraulically decoupled from the underlying aquifer by an intervening unsaturated zone, was discussed above. Examination of the distribution of groundwater elevations (heads), e.g. potentiometric surface mapping, particularly with respect to the stream location and water-surface elevation, may assist in the interpretation of hydrological disconnection. A related issue is the hydraulic conductance of the streambed. Due to an accumulation of fine-grained material and organic debris at the streambed, a zone of permeability lower than that of the underlying aquifer may develop, which reduces hydrological connection.

Stream and Aquifer Geometry. The simplified stream depletion calculations assumes a linear stream, extending to infinity in both directions past the well. If much of the stream is further from (or closer to) the well than this assumption, e.g. a regional stream curve, depletion will be less (or more). If a well is located so as to impact more than one stream, the total depletion will be more than is calculated for a single stream. If the aquifer comes to an end within a distance influenced by the well, e.g. an alluvial aquifer pinching out at the valley side, there will be less aquifer storage available to the well than is represented by Figure 1 and stream depletion will be enhanced accordingly.

Recommended Approach

The recommended process for evaluation of hydrological connection under the 28:40 criteria follows:

1. Screen for previous determinations of hydrological connection, e.g. the North Platte Decree and PRRIP "green area" maps. These have been endorsed by the relevant parties for specific application under those compliance programs. Similarly, there is a small number of individual well studies of hydrological connection conducted for various development and permitting purposes which may be relevant to a new investigation. If an area/aquifer has been previously determined to qualify as "not hydrologically connected", there may be no need for further evaluation. Contact the WSEO North Platte River Coordinator for details.

2. Assess the hydrogeologic setting as discussed above to determine if "hydrological connection" status is obvious. For example, a near-stream well drawing from a shallow aquifer is almost certainly "connected" under the 28:40 criteria. A far-from-stream well drawing from a deep, confined aquifer is likely to be "not connected".

3. If additional analysis is indicated, compile available aquifer parameter data and apply a simple stream depletion model for general direction and screening-level analysis. The Jenkins (1968) implementation, with an "sdf" calculated directly as sdf = a^2S/T, is appropriate for this step. (The Jenkins reference provides a hand-calculator suitable implementation; an electronic spreadsheet formula is provided in the "Tools" section of this memo; AWAS (2011) provides a computerized implementation with input screens and graphical output.)

4. Consider the potential impact of additional hydrogeologic detail on the screening-level analysis. For example, if the "sdf" parameter is simply being calculated from single values of aquifer transmissivity and storativity, it assumes an extensive, homogeneous aquifer. If the well is in an alluvial aquifer that terminates at the valley wall, stream depletion will be greater than calculated by the screening method. If the simplified method suggests "connected", it is unlikely that more detailed analysis will change that. If the simplified analysis suggests "connected" and there are fracture systems present that would serve to enhance rather than inhibit connection, there may be little point in proceeding (if the hydrological connection issue is just "yes" or "no", rather than the degree of connection). Similarly, if the simplified analysis suggests "not connected" and qualitative consideration of the hydrogeologic setting demonstrates that conclusion would only be bolstered by more detailed analysis, the "yes/no" question may be considered resolved.

5. If ambiguity remains in the "hydrological connected" evaluation (e.g. the simplified calculation indicates a 35% depletion in 40 years, but there is a low-permeability layer between the well's completion interval and the stream), identify the critical hydrogeologic parameters necessary for development of a more accurate conceptual model of the stream / aquifer system and design an investigation program focused on elucidating the key components or parameters affecting the conclusion (e.g. the nature of faulting, groundwater vs. surface water elevations beneath a stream, the permeability of overlying strata, etc.)

6. Develop additional aquifer/stream data, e.g. through research, field mapping, water-level measurement, pump testing, etc. as per the previous step.

7. Apply/construct an appropriate groundwater model to quantitatively assess depletion relationships.

Successive steps in the above outline represent greater commitment of resources. If the desired answer is just a "yes" vs. "no" on "connected?" under the 28:40 criteria, the initial screening steps may be sufficient, depending on how close to the 28% value one falls. If the degree of hydrological connection is required, the analysis required will be proportional to the desired level of accuracy. It is more difficult to predict the difference between 22% and 18% depletion with confidence than the difference between 30% and 10%. However, even with the most complete and expensive analysis possible, the results will be based on projection of impacts in an idealized aquifer system and will include some level of error. Ultimately, the decision to proceed with more elaborate analysis should be based on a realistic assessment of the chances of

usefully refining the conclusions, the resources necessary to conduct a credible investigation, and the potential value of the improved understanding potentially available.

TOOLS

This section provides the references cited above, with annotations, a sampling of the scientific literature related to stream depletion, and spreadsheet equations for calculating stream depletion for the idealized aquifer/stream system of Figure 1.

1. The most common, simplified modeling approach to stream depletion is that based on the work of Glover and Balmer (1954). Jenkins (1968) consolidated basic aquifer parameters into a "stream depletion factor" (sdf) to allow application of Glover's equations to more complex aquifer/stream configurations and to provide simple tables and graphs in lieu of complex mathematical calculations. This same basic formulation is known as "Glover" or "Jenkins" or "sdf" or, in Colorado, the "Schroeder" (Schroeder, 1987) program and its later, modern computer implementation, "AWAS" (2011).

> Glover, Robert J. And Glenn G. Balmer; 1954; River Depletion Resulting From Pumping a Well Near a River; American Geophysical Union, Transactions, Vol. 35, No. 3. This is the seminal paper, of interest as an historical foundation, but long-since supplanted by more tractable publications.
>
> Jenkins, C.T.; 1968; Computation of Rate and Volume of Stream Depletion by Wells; U.S. Geological Survey Techniques of Water-Resources Investigations, Chapter D1, Book 4 - Hydrologic Analysis and Interpretation; basically the same paper as:
>
> Jenkins, C.T.; 1968; Techniques for Computing Rate and Volume of Stream Depletion Near Wells; Groundwater, 6, no. 2, pp. 37-46. Jenkins provides a readily usable explanation and non-computer implementation of basic stream depletion, including accommodation of multiple pumping and recovery periods, and including useful examples.
>
> Missouri Basin States Association; 1982; Technical Paper - Ground Water Depletion (and accompanying maps). This work applied the "sdf" method to the major tributaries of the Missouri River, including the North Platte River below Guernsey Dam.
>
> Schroeder, Dewayne R.; 1987; Analytical Stream Depletion Model; Colorado Division of Water Resources, Office of the State Engineer, Ground Water Software Publication No. 1. This user-interactive BASIC program applied the "Glover" equations (or the "Jenkins" approach if an sdf is independently available) to aquifers with boundaries parallel or perpendicular to the stream. Its DOS shell and primitive graphics have been replaced in the AWAS implementation described below.

AWAS - Alluvial Water Accounting System Ver.1.5.75; 2011. This program was developed by the Integrated Decision Support Group at Colorado State University. The AWAS "Original" mode duplicates Schroeder (1987). The latest version of the program, users manual, a quick tutorial, and the above-referenced Jenkins and Schroeder papers can be downloaded from website: http://www.ids.colostate.edu/projects/idsawas/

With the advent of electronic spreadsheets implementing advanced mathematical functions, the tabled, graphed, or programmed values in these references that relate depletion to sdf can be readily duplicated as single-cell spreadsheet formulas. In an EXCEL™ spreadsheet, for example:

v/Qt =((sdf/(2*t))+1)*ERFC((sdf/(4*t))^0.5)-((sdf/(4*t))^0.5)*(2/(PI()^0.5)*EXP((sdf)/(4*t)))
= the cumulative volume of stream depletion over time t

and,

q/Q = 1-ERF(0,(sdf/(4*t))^0.5) = the instantaneous rate of stream depletion at time t

where,

sdf = a^2S/T = stream depletion factor (days)

and,

a = distance from the well to the stream (ft);
S = specific yield of the intervening aquifer (dimensionless);
T = the transmissivity of the intervening aquifer (ft^2/day);
t = pumping time (days);
q = the rate of stream depletion (ft^3/day);
Q = the rate of well pumping (ft^3/day);
v = cumulative volume of stream depletion (ft^3).

2. Analysis, critique, and refinement of this basic approach is provided in the following journal articles (among many others):

Sophocleous, M., A. Kousis, J.L. Martin, and S.P. Perkins; 1995; Evaluation of Simplified Stream Aquifer Depletion Models for Water Rights Administration; Groundwater, Vol. 33, No. 4 uses a numerical model to evaluate some of the simplifying assumptions of the "sdf" approach. The general conclusion is that the "sdf" methods tend to somewhat overstate stream depletion by near-stream wells.

Hunt, Bruce; 1999; Unsteady Stream Depletion from Ground Water Pumping; Groundwater, Vol. 37, No. 1 addresses depletion of a stream that does not fully penetrate the aquifer and which has an inhibiting streambed layer.

Pattle Delamore Partners Ltd & Environment Canterbury; June, 2000; Guidelines for the Assessment of Groundwater Abstraction Effects on Stream Flow; Environment Canterbury (ROO/11)(ISBN 1-86937-387-1) presents extensions of the "sdf" equations to accommodate additional factors like streambed conductance, more than one stream, and springs.

Miller, Calvin D., Deanna Durnford, Mary R. Halstead, Jon Altenhofen, and Val Flory; 2007; Stream Depletion in Alluvial Valleys Using the SDF Semi-analytical Model; Groundwater, Vol. 45, No. 4, pp: 506-514 provides a lucid discussion of the use of the "sdf" parameter to incorporate limited aquifer deviations from ideal conditions, and offers a refinement to better reflect aquifer boundaries.

Reeves, Howard W.; 2008; STRMDEPL08 - An Extended Version of STRMDEPL with Additional Analytical Solutions to Calculate Streamflow Depletion by Nearby Pumping Wells; U.S. Geological Survey Open-File Report 2008-1166 incorporates analytical equations to accommodate partial penetration, streambed conductance, and leaky aquifer parameters.

3. The references cited above provide approaches that are idealized with respect to the nature of the aquifer – typically homogeneous, isotropic, and unconfined – and the overall aquifer/stream system geometry - e.g. fully-penetrating wells and streams, linear streams and aquifer boundaries, single-layer aquifers. Accommodation of more complex conceptualizations of the stream:aquifer system is generally provided through site-specific numerical modeling. Review of the professional literature will find many site-specific examples.

Appendix E

Summary Statistics for Environmental Water Samples

Laura L. Hallberg, and Melanie L. Clark

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	pH (standard units)	6.7	6.9	7.5	8.1	8.3	7
	Specific conductance (µS/cm)	390	400	402	488	576	7
	Hardness (as $CaCO_3$)	3.9	71.4	131	162	221	7
	Calcium	0.90	20.0	41.0	51.0	72.0	7
	Magnesium	0.40	5.2	8.3	9.0	10.0	7
	Sodium	14.0	21.0	29.0	66.0	140	7
	Potassium	1.5	4.4	4.5	4.7	5.1	7
	Sodium-adsorption ratio (unitless)	0.41	0.72	1.1	3.4	30.9	7
	Alkalinity (as $CaCO_3$)	134	134	156	190	219	7
	Chloride	7.0	7.1	8.1	16.0	20.0	7
	Fluoride	0.20	0.30	0.40	0.40	1.0	7
	Silica	25.0	28.0	28.0	39.0	43.0	7
	Sulfate	23.0	36.0	45.0	61.0	74.0	7
	Total dissolved solids	252	253	269	304	391	7
	Nitrate+nitrite (as N)	--	0.41	0.43	1.3	1.9	5
	Orthophosphate (as P)	--	0.010	0.020	0.030	0.030	3
	Phosphorus, unfiltered (as P)	--	0.030	0.030	0.070	0.070	3
	Boron	--	30.0	40.0	140	140	3
	Selenium	<1.0	--	--	--	--	1
Aquifers in undifferentiated Miocene rocks	Dissolved oxygen	0.70	--	3.4	--	5.0	3
	pH (standard units)	7.1	7.4	7.8	8.1	8.4	31
	Specific conductance (µS/cm)	132	311	352	796	11,500	30
	Hardness (as $CaCO_3$)	54.0	100	130	180	3,700	26
	Calcium	18.0	29.0	39.0	51.0	900	27
	Magnesium	2.3	4.8	6.7	16.0	350	26
	Sodium	6.0	15.0	25.5	38.0	1,100	28
	Potassium	0.20	2.4	4.7	6.2	48.0	27
	Sodium-adsorption ratio (unitless)	0.40	0.59	0.95	1.5	7.9	24
	Alkalinity (as $CaCO_3$)	64.0	108	142	184	460	28
	Bromide	0.13	--	--	--	--	1
	Chloride	1.0	3.3	6.4	11.0	3,900	28
	Fluoride	0.10	0.30	0.40	0.50	1.1	27
	Silica	1.9	24.0	45.0	53.0	67.0	26
	Sulfate	0.60	14.0	27.5	57.5	440	28
	Total dissolved solids	90.0	198	249	320	6,660	28
	Ammonia (as N)	--	0.011	0.032	0.065	2.6	8
	Ammonia+organic nitrogen, unfiltered (as N)	0.16	--	--	--	--	1
	Ammonia, unfiltered (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	--	0.40	0.53	1.5	13.7	18
	Nitrate+nitrite, unfiltered (as N)	0.90	--	--	--	--	1
	Nitrate (as N)	--	0.065	0.15	0.37	3.6	16

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in undifferentiated Miocene rocks—Continued	Organic nitrogen, unfiltered (as N)	0.16	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	1.1	--	--	--	--	1
	Orthophosphate (as P)	--	0.011	0.018	0.025	0.12	8
	Phosphorus, unfiltered (as P)	--	0.030	0.070	0.25	0.65	11
	Arsenic	--	1.0	1.0	5.0	7.0	5
	Boron	--	37.9	76.3	170	460	7
	Cobalt	0.25	--	--	--	--	1
	Iron, unfiltered	--	30.0	50.0	3,000	4,200	7
	Lithium	28.6	--	--	--	30.0	2
	Manganese, unfiltered	30.0	--	--	--	--	1
	Molybdenum	2.0	--	--	--	6.6	2
	Selenium	--	1.3	1.6	1.9	2.0	5
	Strontium	443	--	--	--	--	1
	Vanadium	1.2	--	--	--	3.3	2
	Gross alpha radioactivity (picocuries per liter)	17.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	--	4.7	7.4	8.5	9.0	4
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	373	401	526	642	4
	Uranium	--	5.2	5.2	10.0	51.0	5
White River aquifer and confining unit	pH (standard units)	7.3	7.5	7.5	7.6	7.6	5
	Specific conductance (µS/cm)	300	346	382	530	690	5
	Hardness (as $CaCO_3$)	81.4	120	179	225	275	5
	Calcium	27.0	35.0	57.0	77.0	87.0	5
	Magnesium	3.4	7.3	7.9	8.9	14.0	5
	Sodium	9.8	12.0	17.0	23.0	49.0	5
	Potassium	2.9	3.4	4.1	6.2	8.5	5
	Sodium-adsorption ratio (unitless)	0.32	0.35	0.60	0.70	2.4	5
	Alkalinity (as $CaCO_3$)	148	149	151	164	201	5
	Chloride	3.9	5.3	6.2	6.3	8.1	5
	Fluoride	0.30	0.30	0.30	0.30	0.70	5
	Silica	24.0	42.0	44.0	45.0	67.0	5
	Sulfate	5.8	26.0	47.0	86.0	110	5
	Total dissolved solids	216	271	282	329	397	5
	Nitrate+nitrite (as N)	--	0.25	0.42	0.80	1.0	4
	Phosphorus, unfiltered (as P)	--	0.015	0.030	0.045	0.050	4
	Selenium	5.0	--	--	--	--	1
Wagon Bed aquifer and confining unit	pH (standard units)	7.8	--	--	--	8.3	2
	Specific conductance (µS/cm)	362	--	--	--	510	2
	Hardness (as $CaCO_3$)	159	--	--	--	160	2

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wagon Bed aquifer and confining unit—Continued	Calcium	53.0	--	--	--	55.0	2
	Magnesium	5.6	--	--	--	6.5	2
	Sodium	7.0	--	--	--	46.0	2
	Potassium	3.6	--	--	--	3.6	2
	Sodium-adsorption ratio (unitless)	0.24	--	--	--	1.6	2
	Alkalinity (as $CaCO_3$)	159	--	--	--	181	2
	Chloride	3.6	--	--	--	7.6	2
	Fluoride	0.20	--	--	--	0.40	2
	Silica	32.0	--	--	--	46.0	2
	Sulfate	9.1	--	--	--	77.0	2
	Total dissolved solids	233	--	--	--	331	2
	Ammonia (as N)	0.020	--	--	--	0.040	2
	Nitrate+nitrite (as N)	0.066	--	--	--	0.75	2
	Nitrate (as N)	<0.066	--	--	--	0.74	2
	Nitrite (as N)	<0.010	--	--	--	0.010	2
	Orthophosphate (as P)	0.020	--	--	--	0.050	2
	Phosphorus, unfiltered (as P)	0.040	--	--	--	0.060	2
	Selenium	<1.0	--	--	--	<4.0	2
Wind River aquifer	Specific conductance (µS/cm)	320	--	--	--	--	1
Frontier aquifer	pH (standard units)	7.9	--	--	--	8.6	2
	Specific conductance (µS/cm)	2,000	--	2,330	--	3,740	3
	Hardness (as $CaCO_3$)	10.0	--	1,000	--	1,600	3
	Calcium	2.9	--	278	--	442	3
	Magnesium	0.70	--	77.0	--	116	3
	Sodium	166	--	351	--	461	3
	Potassium	1.2	--	5.7	--	6.1	3
	Sodium-adsorption ratio (unitless)	2.3	--	3.8	--	63.0	3
	Alkalinity (as $CaCO_3$)	234	--	383	--	484	3
	Chloride	9.2	--	35.0	--	73.0	3
	Fluoride	1.2	--	2.0	--	2.1	3
	Silica	3.2	--	11.0	--	19.0	3
	Sulfate	487	--	900	--	2,000	3
	Total dissolved solids	1,280	--	1,740	--	3,330	3
	Nitrate+nitrite (as N)	1.2	--	--	--	--	1
	Nitrate (as N)	0.090	--	--	--	0.70	2
	Boron	--	380	470	1,100	1,100	3
	Iron, unfiltered	480	--	--	--	590	2
Cloverly aquifer	Dissolved oxygen	7.0	--	--	--	--	1
	pH (standard units)	7.3	--	7.4	--	8.3	3
	Specific conductance (µS/cm)	378	--	779	--	2,670	3
	Hardness (as $CaCO_3$)	4.0	--	168	--	1,800	3
	Calcium	1.4	--	47.6	--	471	3

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cloverly aquifer—Continued	Magnesium	0.10	--	11.8	--	159	3
	Sodium	9.7	--	40.0	--	184	3
	Potassium	0.20	--	2.0	--	2.8	3
	Sodium-adsorption ratio (unitless)	0.33	--	0.41	--	40.5	3
	Alkalinity (as $CaCO_3$)	101	--	125	--	287	3
	Bromide	0.030	--	--	--	--	1
	Chloride	3.7	--	8.2	--	11.0	3
	Fluoride	0.19	--	0.90	--	1.6	3
	Silica	12.0	--	12.3	--	14.0	3
	Sulfate	82.8	--	98.0	--	1,680	3
	Total dissolved solids	241	--	484	--	2,680	3
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	0.26	--	--	--	--	1
	Nitrate (as N)	<0.26	--	--	--	1.1	2
	Nitrite (as N)	<0.008	--	--	--	--	1
	Orthophosphate (as P)	<0.020	--	--	--	--	1
	Aluminum	<1.6	--	--	--	--	1
	Antimony	<0.30	--	--	--	--	1
	Arsenic	0.30	--	--	--	--	1
	Barium	57.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	--	56.0	100	340	340	3
	Cadmium	0.02	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.14	--	--	--	--	1
	Copper	0.80	--	--	--	--	1
	Iron	<8.0	--	--	--	--	1
	Iron, unfiltered	130	--	--	--	--	1
	Lead	<0.08	--	--	--	--	1
	Lithium	18.7	--	--	--	--	1
	Manganese	<0.20	--	--	--	--	1
	Molybdenum	2.4	--	--	--	--	1
	Nickel	2.0	--	--	--	--	1
	Selenium	2.6	--	--	--	--	1
	Strontium	719	--	--	--	--	1
	Vanadium	0.30	--	--	--	--	1
	Zinc	0.50	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	6,940	--	--	--	--	1
	Uranium	8.2	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit	pH (standard units)	7.1	--	7.3	--	7.4	3
	Specific conductance (µS/cm)	640	--	--	--	920	2
	Calcium	63.5	--	77.3	--	77.8	3
	Magnesium	25.6	--	48.3	--	49.0	3
	Sodium	18.5	--	19.0	--	24.0	3
	Potassium	2.7	--	3.9	--	4.1	3
	Alkalinity (as $CaCO_3$)	169	--	215	--	249	3
	Chloride	4.7	--	6.3	--	7.2	3
	Fluoride	0.17	--	0.20	--	0.21	3
	Silica	4.4	--	5.6	--	6.1	3
	Sulfate	110	--	155	--	185	3
	Total dissolved solids	315	--	445	--	450	3
Sundance aquifer	pH (standard units)	8.0	--	--	--	--	1
	Hardness (as $CaCO_3$)	180	--	--	--	--	1
	Calcium	40.0	--	--	--	--	1
	Magnesium	20.0	--	--	--	--	1
	Sodium	170	--	--	--	--	1
	Potassium	2.3	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	5.5	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	210	--	--	--	--	1
	Chloride	7.4	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	300	--	--	--	--	1
	Total dissolved solids	680	--	--	--	--	1
	Ammonia+organic nitrogen, unfiltered (as N)	0.33	--	--	--	--	1
	Ammonia, unfiltered (as N)	0.11	--	--	--	--	1
	Nitrate+nitrite, unfiltered (as N)	0.040	--	--	--	--	1
	Organic nitrogen, unfiltered (as N)	0.22	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.37	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.010	--	--	--	--	1
	Aluminum	20.0	--	--	--	--	1
	Arsenic	1.0	--	--	--	--	1
	Beryllium	<10.0	--	--	--	--	1
	Boron	200	--	--	--	--	1
	Iron	30.0	--	--	--	--	1
	Iron, unfiltered	1,200	--	--	--	--	1
	Lithium	60.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Manganese, unfiltered	30.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Sundance aquifer—Continued	Molybdenum	6.0	--	--	--	--	1
	Selenium	1.0	--	--	--	--	1
	Zinc	<20.0	--	--	--	--	1
Chugwater aquifer and confining unit	Dissolved oxygen	5.0	--	--	--	--	1
	pH (standard units)	7.4	--	7.8	--	7.8	3
	Specific conductance (µS/cm)	447	707	1,710	2,490	2,520	4
	Hardness (as $CaCO_3$)	220	385	1,080	1,750	1,890	4
	Calcium	57.0	109	310	535	611	4
	Magnesium	20.0	28.5	62.0	101	116	4
	Sodium	7.2	7.9	13.6	31.3	44.0	4
	Potassium	1.4	1.6	2.9	4.1	4.2	4
	Sodium-adsorption ratio (unitless)	0.13	0.16	0.22	0.37	0.48	4
	Alkalinity (as $CaCO_3$)	95.1	108	153	194	205	4
	Bromide	0.050	--	--	--	--	1
	Chloride	1.4	1.6	3.7	15.8	26.0	4
	Fluoride	0.20	0.20	0.35	0.75	1.0	4
	Silica	8.1	8.6	11.6	15.5	17.0	4
	Sulfate	33.0	194	938	1,530	1,530	4
	Total dissolved solids	264	499	1,500	2,350	2,440	4
	Ammonia (as N)	0.050	--	--	--	--	1
	Nitrate+nitrite (as N)	0.56	--	--	--	--	1
	Nitrite (as N)	<0.008	--	--	--	--	1
	Orthophosphate (as P)	<0.020	--	--	--	--	1
	Aluminum	<1.6	--	--	--	--	1
	Antimony	<0.30	--	--	--	--	1
	Arsenic	1.4	--	--	--	--	1
	Barium	8.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	--	8.2	78.0	273	400	4
	Cadmium	<0.04	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	1.0	--	--	--	--	1
	Copper	5.1	--	--	--	--	1
	Iron	<24.0	--	--	--	--	1
	Lead	<0.08	--	--	--	--	1
	Lithium	28.0	--	--	--	--	1
	Manganese	1.5	--	--	--	--	1
	Molybdenum	6.0	--	--	--	--	1
	Nickel	16.5	--	--	--	--	1
	Selenium	13.3	--	--	--	--	1
	Strontium	8,260	--	--	--	--	1
	Vanadium	3.1	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater aquifer and confining unit—Continued	Zinc	2.9	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	1,150	--	--	--	--	1
	Uranium	7.6	--	--	--	--	1
Alcova confining unit within Chugwater aquifer and confining unit	pH (standard units)	6.8	--	--	--	7.8	2
	Specific conductance (µS/cm)	627	--	--	--	660	2
	Calcium	48.5	--	--	--	83.9	2
	Magnesium	28.8	--	--	--	45.3	2
	Sodium	16.6	--	--	--	24.7	2
	Potassium	1.2	--	--	--	1.6	2
	Alkalinity (as $CaCO_3$)	169	--	--	--	211	2
	Chloride	14.3	--	--	--	17.5	2
	Fluoride	0.15	--	--	--	0.17	2
	Silica	5.1	--	--	--	5.1	2
	Sulfate	97.9	--	--	--	179	2
	Total dissolved solids	304	--	--	--	453	2
Goose Egg aquifer and confining unit	Dissolved oxygen	0.60	--	--	--	3.3	2
	pH (standard units)	7.1	7.2	7.7	8.0	8.2	5
	Specific conductance (µS/cm)	1,170	2,230	2,680	3,170	3,220	7
	Hardness (as $CaCO_3$)	1,440	--	1,870	--	1,940	3
	Calcium	247	402	550	578	598	7
	Magnesium	56.3	76.7	105	121	212	7
	Sodium	11.5	13.7	20.1	154	200	7
	Potassium	1.3	2.6	4.6	6.8	8.4	7
	Sodium-adsorption ratio (unitless)	0.14	--	--	--	1.8	2
	Alkalinity (as $CaCO_3$)	121	123	138	184	189	7
	Bromide	0.10	--	--	--	0.22	2
	Chloride	3.8	5.6	10.3	35.2	189	7
	Fluoride	0.17	0.19	0.29	0.50	1.3	7
	Silica	4.7	5.7	6.5	11.2	13.2	6
	Sulfate	697	1,280	1,500	1,920	2,040	7
	Total dissolved solids	1,090	2,240	2,430	2,740	3,220	7
	Ammonia (as N)	0.040	--	--	--	0.060	2
	Nitrate (as N)	<0.060	--	--	--	<2.6	2
	Nitrite (as N)	<0.008	--	--	--	<0.008	2
	Orthophosphate (as P)	<0.020	--	--	--	<0.020	2
	Aluminum	<3.2	--	--	--	<3.2	2
	Antimony	<0.60	--	--	--	<0.60	2
	Arsenic	0.90	--	--	--	1.9	2
	Barium	8.0	--	--	--	10.0	2
	Beryllium	<0.12	--	--	--	<0.12	2
	Boron	--	135	191	865	865	3

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Goose Egg aquifer and confining unit—Continued	Cadmium	<0.07	--	--	--	<0.07	2
	Chromium	<0.80	--	--	--	<0.80	2
	Cobalt	1.1	--	--	--	2.6	2
	Copper	6.2	--	--	--	8.0	2
	Iron	21.0	--	--	--	47.0	2
	Lead	<0.16	--	--	--	<0.16	2
	Lithium	50.4	--	--	--	75.6	2
	Manganese	24.7	--	--	--	37.8	2
	Molybdenum	5.0	--	--	--	7.5	2
	Nickel	8.3	--	--	--	28.6	2
	Selenium	1.4	--	--	--	11.8	2
	Strontium	4,330	--	--	--	5,190	2
	Vanadium	<0.30	--	--	--	1.1	2
	Zinc	8.2	--	--	--	26.1	2
	Radon-222, unfiltered (picocuries per liter)	280	--	--	--	1,340	2
	Uranium	11.5	--	--	--	13.9	2
Forelle Limestone	pH (standard units)	8.1	--	--	--	--	1
	Specific conductance (µS/cm)	334	--	--	--	--	1
	Hardness (as $CaCO_3$)	190	--	--	--	--	1
	Calcium	43.0	--	--	--	--	1
	Magnesium	19.0	--	--	--	--	1
	Sodium	3.8	--	--	--	--	1
	Potassium	0.10	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.10	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	179	--	--	--	--	1
	Chloride	0.70	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	12.0	--	--	--	--	1
	Sulfate	7.7	--	--	--	--	1
	Total dissolved solids	216	--	--	--	--	1
	Nitrate (as N)	0.70	--	--	--	--	1
	Iron, unfiltered	10.0	--	--	--	--	1
Satanka confining unit	Specific conductance (µS/cm)	1,660	--	--	--	--	1
	Hardness (as $CaCO_3$)	940	--	--	--	--	1
	Calcium	232	--	--	--	--	1
	Magnesium	88.0	--	--	--	--	1
	Sodium	35.0	--	--	--	--	1
	Potassium	3.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.50	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	128	--	--	--	--	1
	Chloride	25.0	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Satanka confining unit—Continued	Fluoride	1.0	--	--	--	--	1
	Silica	23.0	--	--	--	--	1
	Sulfate	840	--	--	--	--	1
	Total dissolved solids	1,330	--	--	--	--	1
	Nitrate (as N)	0.84	--	--	--	--	1
	Boron	210	--	--	--	--	1
	Iron, unfiltered	20.0	--	--	--	--	1
Casper aquifer	pH (standard units)	7.6	7.7	8.1	8.1	8.1	6
	Specific conductance (µS/cm)	557	602	680	1,200	2,020	8
	Hardness (as $CaCO_3$)	233	240	270	404	1,240	7
	Calcium	36.0	56.0	60.0	72.1	394	8
	Magnesium	22.0	23.5	30.9	49.0	62.8	8
	Sodium	5.1	26.5	38.9	46.5	169	8
	Potassium	1.8	2.5	3.2	4.3	11.8	8
	Sodium-adsorption ratio (unitless)	0.67	--	--	--	1.4	2
	Alkalinity (as $CaCO_3$)	143	160	185	226	251	8
	Chloride	6.2	22.4	39.3	50.1	56.0	8
	Fluoride	0.30	0.50	0.67	1.1	1.3	6
	Silica	10.0	10.5	11.3	17.8	24.0	4
	Sulfate	61.0	97.0	121	362	1,010	8
	Total dissolved solids	276	372	396	820	1,880	8
	Ammonia (as N)	<0.10	--	--	--	<1.0	2
	Nitrate+nitrite (as N)	0.27	--	--	--	1.6	2
	Nitrite (as N)	<0.010	--	--	--	--	1
	Aluminum	<100	--	--	--	--	1
	Boron	--	62.0	184	300	313	7
	Iron, unfiltered	40.0	--	--	--	50.0	2
	Molybdenum	<100	--	--	--	1,000	2
	Nickel	<40.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	19.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	10.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	5.6	--	--	--	--	1
	Uranium	41.0	--	--	--	--	1
Tensleep aquifer	Dissolved oxygen	5.8	--	--	--	--	1
	pH (standard units)	6.5	7.2	7.7	8.0	8.2	17
	Specific conductance (µS/cm)	300	341	427	665	2,360	16
	Hardness (as $CaCO_3$)	170	180	200	255	1,520	9
	Calcium	47.6	51.1	64.0	98.0	371	16
	Magnesium	11.0	15.0	17.8	35.5	145	16
	Sodium	2.7	3.1	4.0	5.9	170	16

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Tensleep aquifer—Continued	Potassium	0.10	0.35	1.1	3.5	10.0	16
	Sodium-adsorption ratio (unitless)	0.080	0.10	0.10	0.13	3.6	9
	Alkalinity (as $CaCO_3$)	84.0	168	176	201	592	16
	Bromide	0.030	--	--	--	0.040	2
	Chloride	0.70	1.2	5.1	8.0	240	15
	Fluoride	0.090	0.15	0.18	0.20	2.4	16
	Silica	4.1	4.8	8.3	11.5	36.0	16
	Sulfate	6.6	8.4	50.9	200	1,100	16
	Total dissolved solids	165	195	260	450	2,210	16
	Ammonia (as N)	<0.040	--	--	--	0.20	2
	Ammonia+organic nitrogen, unfiltered (as N)	0.21	--	--	--	--	1
	Ammonia, unfiltered (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	<0.060	--	--	--	1.3	2
	Nitrate+nitrite, unfiltered (as N)	0.050	--	--	--	--	1
	Nitrate (as N)	--	0.21	0.36	0.63	0.70	8
	Nitrite (as N)	<0.008	--	--	--	<0.008	2
	Organic nitrogen, unfiltered (as N)	0.21	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.26	--	--	--	--	1
	Orthophosphate (as P)	<0.020	--	--	--	<0.020	2
	Phosphorus, unfiltered (as P)	0.010	--	--	--	--	1
	Arsenic	--	0.20	0.20	4.0	4.0	3
	Barium	<0.05	--	--	--	7.0	2
	Boron	--	13.2	70.0	152	180	4
	Cadmium	0.02	--	--	--	0.04	2
	Cobalt	0.18	--	--	--	1.3	2
	Manganese, unfiltered	20.0	--	--	--	--	1
	Mercury	<0.50	--	--	--	--	1
	Nickel	1.7	--	--	--	8.0	2
	Strontium	150	--	--	--	1,620	2
	Iron, unfiltered	--	10.0	40.0	50.0	90.0	7
	Lithium	--	4.8	39.0	120	120	3
	Manganese	--	0.40	20.0	71.9	71.9	3
	Vanadium	--	0.30	1.4	3.5	3.5	3
	Radium-226 (picocuries per liter)	0.18	--	--	--	--	1
	Radium-228 (picocuries per liter)	0.03	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	120	650	6,080	6,080	3
	Uranium	0.02	--	--	--	2.9	2
Madison aquifer	Dissolved oxygen	5.5	--	--	--	--	1
	pH (standard units)	7.8	--	--	--	8.3	2
	Specific conductance (µS/cm)	295	--	--	--	406	2

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer—Continued	Hardness (as $CaCO_3$)	160	--	--	--	206	2
	Calcium	46.0	--	--	--	55.7	2
	Magnesium	12.0	--	--	--	16.2	2
	Sodium	1.0	--	--	--	3.6	2
	Potassium	0.40	--	--	--	0.61	2
	Sodium-adsorption ratio (unitless)	0.030	--	--	--	0.11	2
	Alkalinity (as $CaCO_3$)	152	--	--	--	186	2
	Bromide	0.090	--	--	--	--	1
	Chloride	0.60	--	--	--	8.1	2
	Fluoride	0.10	--	--	--	0.17	2
	Silica	6.1	--	--	--	9.1	2
	Sulfate	5.8	--	--	--	15.2	2
	Total dissolved solids	170	--	--	--	233	2
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	1.7	--	--	--	--	1
	Nitrate (as N)	<1.7	--	--	--	--	1
	Nitrite (as N)	<0.008	--	--	--	--	1
	Aluminum	<1.6	--	--	--	--	1
	Antimony	<0.30	--	--	--	--	1
	Arsenic	0.50	--	--	--	--	1
	Barium	67.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	9.0	--	--	--	10.0	2
	Cadmium	<0.04	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.17	--	--	--	--	1
	Copper	8.2	--	--	--	--	1
	Iron	<8.0	--	--	--	--	1
	Iron, unfiltered	80.0	--	--	--	--	1
	Lead	0.07	--	--	--	--	1
	Lithium	2.9	--	--	--	--	1
	Manganese	<0.20	--	--	--	--	1
	Molybdenum	0.60	--	--	--	--	1
	Nickel	0.71	--	--	--	--	1
	Selenium	1.4	--	--	--	--	1
	Strontium	125	--	--	--	--	1
	Vanadium	2.0	--	--	--	--	1
	Zinc	9.3	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	610	--	--	--	--	1
	Uranium	2.3	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in undifferentiated Cambrian rocks	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	353	--	--	--	--	1
	Hardness (as $CaCO_3$)	170	--	--	--	--	1
	Calcium	46.0	--	--	--	--	1
	Magnesium	13.0	--	--	--	--	1
	Sodium	9.3	--	--	--	--	1
	Potassium	1.4	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.30	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	156	--	--	--	--	1
	Chloride	3.0	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	7.8	--	--	--	--	1
	Sulfate	24.0	--	--	--	--	1
	Total dissolved solids	200	--	--	--	--	1
	Nitrate (as N)	0.25	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Iron, unfiltered	70.0	--	--	--	--	1
Flathead aquifer	pH (standard units)	7.1	--	--	--	--	1
	Specific conductance (µS/cm)	162	--	--	--	--	1
	Hardness (as $CaCO_3$)	71.0	--	--	--	--	1
	Calcium	21.0	--	--	--	--	1
	Magnesium	4.5	--	--	--	--	1
	Sodium	5.3	--	--	--	--	1
	Potassium	0.90	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.27	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	73.0	--	--	--	--	1
	Chloride	0.10	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	15.0	--	--	--	--	1
	Sulfate	6.5	--	--	--	--	1
	Total dissolved solids	99.0	--	--	--	--	1
	Nitrate+nitrite (as N)	0.40	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.10	--	--	--	--	1
Precambrian basal confining unit	Dissolved oxygen	3.9	--	--	--	8.6	2
	pH (standard units)	6.6	6.9	7.0	7.6	8.1	20
	Specific conductance (µS/cm)	50.0	138	212	272	1,100	20
	Hardness (as $CaCO_3$)	42.0	52.7	101	128	265	12
	Calcium	5.9	13.8	31.0	39.0	70.0	13
	Magnesium	1.5	3.2	4.8	5.8	22.0	13
	Sodium	2.0	5.5	6.8	8.0	130	13
	Potassium	0.33	0.90	1.8	1.9	15.0	13
	Sodium-adsorption ratio (unitless)	0.07	0.30	0.31	0.38	3.5	12

Appendix E1. Summary statistics for environmental water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Precambrian basal confining unit—Continued	Alkalinity (as $CaCO_3$)	21.9	58.0	90.0	130	179	13
	Bromide	0.070	--	--	--	--	1
	Chloride	0.10	0.68	0.80	4.3	120	13
	Fluoride	0.070	0.20	0.20	0.30	1.8	13
	Silica	8.0	14.7	17.3	21.0	28.0	13
	Sulfate	0.80	4.8	9.5	17.0	220	13
	Total dissolved solids	34.0	81.0	140	176	714	13
	Nitrate+nitrite (as N)	--	0.20	0.28	0.42	1.2	10
	Phosphorus, unfiltered (as P)	--	0.004	0.008	0.025	0.030	8
	Antimony	0.07	--	--	--	<0.30	2
	Arsenic	--	0.50	1.3	2.5	3.0	4
	Barium	--	17.0	21.0	29.0	51.0	5
	Boron	--	10.0	20.0	40.0	44.0	5
	Copper	--	1.0	1.3	1.5	2.3	5
	Iron	--	10.0	11.0	17.0	100	5
	Iron, unfiltered	<10.0	--	--	--	120	2
	Lithium	--	8.0	14.0	18.8	21.0	5
	Mercury	<0.10	--	--	--	<0.10	2
	Strontium	--	140	140	250	316	5
	Vanadium	--	1.3	1.6	6.0	6.0	3
	Gross alpha radioactivity (picocuries per liter)	25.4	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	7.8	--	--	--	--	1
	Radium-228 (picocuries per liter)	2.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	2,340	--	--	--	3,790	2
	Tritium, unfiltered (picocuries per liter)	9.0	--	--	--	--	1
	Uranium	1.6	--	--	--	7.1	2

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Dissolved oxygen	0.10	0.10	0.20	3.0	8.2	9
	pH (standard units)	6.5	7.2	7.3	7.8	9.0	26
	Specific conductance (µS/cm)	30.0	440	658	1,100	5,930	35
	Hardness (as $CaCO_3$)	11.6	150	220	350	2,400	25
	Calcium	3.3	38.0	59.0	103	546	25
	Magnesium	0.82	9.4	15.0	34.0	245	25
	Sodium	1.1	22.0	39.0	84.0	736	25
	Potassium	0.31	1.7	2.8	4.0	20.0	25
	Sodium-adsorption ratio (unitless)	0.11	0.70	0.99	1.8	6.9	25
	Alkalinity (as $CaCO_3$)	12.0	156	187	243	536	25
	Chloride	0.10	5.5	12.0	33.0	570	25
	Fluoride	0.10	0.30	0.50	0.70	2.8	25
	Silica	0.40	12.0	15.0	19.0	36.0	25
	Sulfate	0.80	41.0	101	232	2,410	25
	Total dissolved solids	28.0	288	394	725	5,840	25
	Ammonia (as N)	--	0.013	0.023	0.050	0.090	10
	Nitrate+nitrite (as N)	--	0.090	0.53	2.4	32.2	11
	Nitrate (as N)	--	0.039	0.20	1.0	35.0	28
	Nitrite (as N)	--	0.001	0.003	0.009	0.58	10
	Orthophosphate (as P)	--	0.008	0.013	0.020	0.070	10
	Aluminum	9.7	--	--	--	--	1
	Antimony	<0.30	--	--	--	--	1
	Arsenic	<0.30	--	--	--	--	1
	Barium	5.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	--	40.0	100	190	440	19
	Cadmium	<0.04	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.04	--	--	--	--	1
	Copper	1.9	--	--	--	--	1
	Iron	32.0	--	--	--	--	1
	Iron, unfiltered	--	130	295	650	1,400	14
	Lead	0.29	--	--	--	--	1
	Lithium	<0.50	--	--	--	--	1
	Manganese	0.90	--	--	--	--	1
	Molybdenum	<0.30	--	--	--	--	1
	Nickel	0.38	--	--	--	--	1
	Selenium	<0.50	--	--	--	--	1
	Strontium	12.3	--	--	--	--	1
	Vanadium	0.20	--	--	--	--	1
	Zinc	9.5	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers—Continued	Radon-222, unfiltered (picocuries per liter)	--	781	1,570	2,890	3,570	4
	Uranium	0.06	--	--	--	--	1
Quaternary terrace-deposit aquifers	pH (standard units)	7.5	7.8	7.9	8.1	8.1	5
	Specific conductance (µS/cm)	287	499	714	758	800	4
	Hardness (as $CaCO_3$)	103	167	174	212	337	5
	Calcium	8.2	28.0	33.0	40.0	73.4	5
	Magnesium	16.0	20.0	25.0	31.0	37.2	5
	Sodium	17.0	43.5	55.0	65.0	80.0	5
	Potassium	0.93	1.2	3.0	3.1	4.4	5
	Sodium-adsorption ratio (unitless)	0.73	1.0	1.8	2.2	2.4	5
	Alkalinity (as $CaCO_3$)	142	165	180	296	409	5
	Chloride	1.8	8.2	8.9	9.8	11.0	5
	Fluoride	0.70	0.86	0.90	1.2	2.2	5
	Silica	1.0	2.1	7.3	17.2	23.0	5
	Sulfate	20.0	27.0	32.0	171	220	5
	Total dissolved solids	158	360	368	392	512	5
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	1.5	--	--	--	--	1
	Nitrate (as N)	<1.5	--	--	--	--	1
	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	0.020	--	--	--	--	1
	Boron	--	90.0	100	120	120	3
	Radon-222, unfiltered (picocuries per liter)	890	--	--	--	--	1
Quaternary glacial-deposit aquifers	pH (standard units)	7.1	--	--	--	--	1
	Specific conductance (µS/cm)	109	--	--	--	--	1
	Hardness (as $CaCO_3$)	20.0	--	--	--	--	1
	Calcium	7.6	--	--	--	--	1
	Magnesium	0.10	--	--	--	--	1
	Sodium	19.0	--	--	--	--	1
	Potassium	2.2	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	1.9	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	51.0	--	--	--	--	1
	Chloride	3.5	--	--	--	--	1
	Fluoride	0.30	--	--	--	--	1
	Silica	5.7	--	--	--	--	1
	Sulfate	16.0	--	--	--	--	1
	Total dissolved solids	92.0	--	--	--	--	1
	Boron	40.0	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in undifferentiated Miocene rocks	pH (standard units)	7.7	--	--	--	9.6	2
	Specific conductance (µS/cm)	420	--	--	--	525	2
	Hardness (as $CaCO_3$)	4.2	--	--	--	136	2
	Calcium	1.1	--	--	--	43.0	2
	Magnesium	0.35	--	--	--	6.9	2
	Sodium	37.0	--	--	--	110	2
	Potassium	1.6	--	--	--	6.9	2
	Sodium-adsorption ratio (unitless)	1.4	--	--	--	23.4	2
	Alkalinity (as $CaCO_3$)	150	--	--	--	171	2
	Chloride	14.0	--	--	--	27.0	2
	Fluoride	0.40	--	--	--	2.9	2
	Silica	24.0	--	--	--	45.0	2
	Sulfate	49.0	--	--	--	51.0	2
	Total dissolved solids	306	--	--	--	308	2
	Nitrate+nitrite (as N)	<0.10	--	--	--	0.20	2
	Phosphorus, unfiltered (as P)	<0.010	--	--	--	0.040	2
Browns Park aquifer	Dissolved oxygen	6.6	--	--	--	8.6	2
	pH (standard units)	7.0	7.5	7.7	8.0	9.4	61
	Specific conductance (µS/cm)	214	331	563	1,090	3,410	53
	Hardness (as $CaCO_3$)	19.0	120	190	310	2,000	50
	Calcium	6.6	36.5	54.5	81.5	646	56
	Magnesium	0.50	4.8	8.2	18.7	147	55
	Sodium	3.3	14.1	38.5	130	453	58
	Potassium	0.80	2.4	4.2	6.9	29.0	54
	Sodium-adsorption ratio (unitless)	0.10	0.45	1.3	4.3	23.0	36
	Alkalinity (as $CaCO_3$)	34.0	112	150	183	410	57
	Bromide	0.060	--	--	--	0.11	2
	Chloride	0.90	6.0	11.0	77.0	511	57
	Fluoride	0.20	0.45	0.60	1.1	10.8	56
	Silica	4.4	22.0	39.0	50.0	67.7	43
	Sulfate	3.4	23.0	90.0	340	1,980	59
	Total dissolved solids	153	236	385	718	3,410	61
	Ammonia+organic nitrogen, unfiltered (as N)	0.30	--	--	--	--	1
	Ammonia, unfiltered (as N)	0.25	--	--	--	--	1
	Nitrate+nitrite (as N)	--	0.025	0.20	0.70	12.0	11
	Nitrate+nitrite, unfiltered (as N)	<0.10	--	--	--	--	1
	Nitrate (as N)	--	0.019	0.066	0.23	2.3	35
	Organic nitrogen, unfiltered (as N)	0.050	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.30	--	--	--	--	1
	Orthophosphate (as P)	<0.010	--	--	--	0.030	2

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Browns Park aquifer—Continued	Phosphorus (as P)	0.080	--	--	--	--	1
	Phosphorus, unfiltered (as P)	--	0.050	0.060	0.070	0.10	5
	Arsenic	--	1.4	3.0	5.5	21.1	20
	Barium	--	50.7	83.3	137	200	12
	Boron	--	37.0	86.2	290	1,400	36
	Chromium	--	0.82	1.1	1.5	2.0	14
	Cobalt	0.11	--	--	--	0.15	2
	Copper	--	2.4	5.1	10.0	66.0	13
	Iron	--	3.5	13.8	160	310	12
	Iron, unfiltered	--	44.5	120	220	530	16
	Lead	--	0.11	0.32	0.88	4.0	16
	Lithium	--	15.1	35.8	140	140	3
	Manganese	--	4.7	40.0	110	300	15
	Manganese, unfiltered	90.0	--	--	--	--	1
	Molybdenum	--	1.1	4.9	10.0	10.0	3
	Nickel	--	0.75	1.0	1.3	2.0	6
	Selenium	--	0.47	0.81	1.4	5.0	19
	Strontium	285	--	--	--	507	2
	Vanadium	2.4	--	--	--	23.5	2
	Zinc	--	2.5	7.6	20.0	330	13
	Gross alpha radioactivity (picocuries per liter)	--	5.4	8.1	12.4	44.4	12
	Gross beta radioactivity (picocuries per liter)	--	3.3	6.7	11.0	17.2	10
	Radium-226 (picocuries per liter)	--	0.080	0.15	0.30	1.2	9
	Radon-222, unfiltered (picocuries per liter)	--	423	772	1,290	1,670	6
	Tritium, unfiltered (picocuries per liter)	39.4	--	--	--	42.9	2
	Uranium	--	3.0	6.0	16.5	35.8	11
White River aquifer and confining unit	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	370	--	--	--	379	2
	Hardness (as $CaCO_3$)	142	--	--	--	150	2
	Calcium	46.0	--	--	--	46.0	2
	Magnesium	6.6	--	--	--	8.8	2
	Sodium	9.3	--	--	--	23.0	2
	Potassium	2.9	--	--	--	3.5	2
	Sodium-adsorption ratio (unitless)	0.33	--	--	--	0.84	2
	Alkalinity (as $CaCO_3$)	160	--	--	--	174	2
	Chloride	1.1	--	--	--	5.6	2
	Fluoride	0.30	--	--	--	0.70	2
	Silica	30.0	--	--	--	44.0	2
	Sulfate	8.2	--	--	--	15.0	2

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
White River aquifer and confining unit—Continued	Total dissolved solids	220	--	--	--	235	2
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	0.19	--	--	--	--	1
	Nitrate (as N)	0.11	--	--	--	<0.19	2
	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	0.020	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.060	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Arsenic	12.0	--	--	--	--	1
	Barium	83.0	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Boron	20.0	--	--	--	40.0	2
	Cadmium	2.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Cobalt	<3.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	17.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Lithium	19.0	--	--	--	--	1
	Manganese	2.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	300	--	--	--	--	1
	Zinc	5.0	--	--	--	--	1
Bridger confining unit	pH (standard units)	9.3	--	--	--	--	1
	Specific conductance (µS/cm)	418	--	--	--	--	1
	Hardness (as $CaCO_3$)	7.1	--	--	--	--	1
	Calcium	2.1	--	--	--	--	1
	Magnesium	0.44	--	--	--	--	1
	Sodium	87.0	--	--	--	--	1
	Potassium	0.60	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	14.3	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	123	--	--	--	--	1
	Chloride	3.3	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	7.6	--	--	--	--	1
	Sulfate	77.0	--	--	--	--	1
	Total dissolved solids	252	--	--	--	--	1
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	<0.050	--	--	--	--	1
	Nitrate (as N)	<0.050	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bridger confining unit—Continued	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	0.030	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.090	--	--	--	--	1
	Aluminum	40.0	--	--	--	--	1
	Arsenic	5.0	--	--	--	--	1
	Barium	24.0	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Boron	40.0	--	--	--	--	1
	Cadmium	1.0	--	--	--	--	1
	Chromium	2.0	--	--	--	--	1
	Cobalt	<3.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	36.0	--	--	--	--	1
	Lead	2.0	--	--	--	--	1
	Lithium	13.0	--	--	--	--	1
	Manganese	2.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	31.0	--	--	--	--	1
	Zinc	<3.0	--	--	--	--	1
Laney confining unit (Laney Member of the Green River Formation)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	900	--	--	--	--	1
	Hardness (as $CaCO_3$)	180	--	--	--	--	1
	Calcium	40.0	--	--	--	--	1
	Magnesium	20.0	--	--	--	--	1
	Sodium	130	--	--	--	--	1
	Potassium	2.1	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	4.2	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	267	--	--	--	--	1
	Chloride	3.4	--	--	--	--	1
	Fluoride	0.70	--	--	--	--	1
	Silica	17.0	--	--	--	--	1
	Sulfate	190	--	--	--	--	1
	Total dissolved solids	563	--	--	--	--	1
	Nitrate+nitrite (as N)	0.010	--	--	--	--	1
	Orthophosphate (as P)	0.010	--	--	--	--	1
	Phosphorus (as P)	<0.010	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.010	--	--	--	--	1
	Boron	50.0	--	--	--	--	1
	Iron	100	--	--	--	--	1
	Manganese	20.0	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Crooks Gap Conglomerate	pH (standard units)	6.6	--	--	--	--	1
	Specific conductance (µS/cm)	106	--	--	--	--	1
	Hardness (as $CaCO_3$)	41.6	--	--	--	--	1
	Calcium	13.0	--	--	--	--	1
	Magnesium	2.2	--	--	--	--	1
	Sodium	3.9	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.26	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	41.0	--	--	--	--	1
	Chloride	0.20	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	7.9	--	--	--	--	1
	Total dissolved solids	73.0	--	--	--	--	1
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	0.45	--	--	--	--	1
	Nitrate (as N)	<0.45	--	--	--	--	1
	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	<0.010	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.010	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Barium	14.0	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
	Cadmium	<1.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Cobalt	<3.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Lithium	5.0	--	--	--	--	1
	Manganese	2.0	--	--	--	--	1
	Mercury	0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	74.0	--	--	--	--	1
	Zinc	7.0	--	--	--	--	1
	Uranium	<0.40	--	--	--	--	1
Battle Spring aquifer	pH (standard units)	7.0	--	--	--	8.0	2
	Specific conductance (µS/cm)	349	--	--	--	359	2
	Hardness (as $CaCO_3$)	104	--	--	--	113	2
	Calcium	35.0	--	--	--	37.0	2

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Battle Spring aquifer-Continued	Magnesium	2.9	--	--	--	6.1	2
	Sodium	9.3	--	--	--	35.0	2
	Potassium	1.1	--	--	--	1.8	2
	Sodium-adsorption ratio (unitless)	0.38	--	--	--	1.5	2
	Alkalinity (as $CaCO_3$)	94.0	--	--	--	138	2
	Chloride	1.9	--	--	--	4.2	2
	Fluoride	0.10	--	--	--	0.20	2
	Silica	13.0	--	--	--	16.0	2
	Sulfate	36.0	--	--	--	45.0	2
	Total dissolved solids	160	--	--	--	225	2
	Ammonia (as N)	<0.010	--	--	--	0.050	2
	Nitrate+nitrite (as N)	<0.050	--	--	--	0.050	2
	Nitrate (as N)	<0.050	--	--	--	<0.050	2
	Nitrite (as N)	<0.010	--	--	--	<0.010	2
	Orthophosphate (as P)	<0.010	--	--	--	<0.010	2
	Phosphorus, unfiltered (as P)	0.040	--	--	--	0.10	2
	Iron	480	--	--	--	--	1
	Manganese	39.0	--	--	--	--	1
Wind River aquifer	Specific conductance (µS/cm)	530	--	1,630	--	8,370	3
	Hardness (as $CaCO_3$)	26.0	--	46.0	--	900	3
	Calcium	7.0	--	12.0	--	267	3
	Magnesium	2.1	--	3.9	--	58.0	3
	Sodium	107	--	345	--	1,780	3
	Potassium	0.60	--	2.0	--	4.2	3
	Sodium-adsorption ratio (unitless)	9.1	--	22.1	--	25.7	3
	Alkalinity (as $CaCO_3$)	98.4	--	164	--	228	3
	Chloride	13.0	--	255	--	894	3
	Fluoride	0.40	--	0.60	--	1.0	3
	Silica	4.9	--	11.0	--	18.0	3
	Sulfate	76.0	--	205	--	3,380	3
	Total dissolved solids	292	--	980	--	6,450	3
	Boron	--	60.0	120	140	140	3
	Iron, unfiltered	--	110	560	940	940	3
Wasatch aquifer	pH (standard units)	7.4	--	--	--	--	1
	Hardness (as $CaCO_3$)	52.3	--	--	--	--	1
	Calcium	14.0	--	--	--	--	1
	Magnesium	4.2	--	--	--	--	1
	Sodium	22.0	--	--	--	--	1
	Potassium	1.7	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	1.3	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	89.0	--	--	--	--	1
	Chloride	0.30	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wasatch aquifer—Continued	Fluoride	0.20	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	11.0	--	--	--	--	1
	Total dissolved solids	126	--	--	--	--	1
	Nitrate+nitrite (as N)	0.10	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.010	--	--	--	--	1
Coalmont Formation	Dissolved oxygen	6.7	--	--	--	--	1
	pH (standard units)	6.8	--	--	--	--	1
	Specific conductance (µS/cm)	162	--	--	--	--	1
	Hardness (as $CaCO_3$)	65.9	--	--	--	--	1
	Calcium	18.7	--	--	--	--	1
	Magnesium	4.6	--	--	--	--	1
	Sodium	7.1	--	--	--	--	1
	Potassium	0.61	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.38	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	74.0	--	--	--	--	1
	Bromide	0.040	--	--	--	--	1
	Chloride	3.5	--	--	--	--	1
	Fluoride	0.31	--	--	--	--	1
	Silica	46.8	--	--	--	--	1
	Sulfate	3.6	--	--	--	--	1
	Total dissolved solids	136	--	--	--	--	1
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	0.71	--	--	--	--	1
	Nitrate (as N)	<0.71	--	--	--	--	1
	Nitrite (as N)	<0.008	--	--	--	--	1
	Orthophosphate (as P)	0.080	--	--	--	--	1
	Aluminum	<1.0	--	--	--	--	1
	Antimony	<0.05	--	--	--	--	1
	Arsenic	0.70	--	--	--	--	1
	Barium	94.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	9.0	--	--	--	--	1
	Cadmium	<0.04	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.05	--	--	--	--	1
	Copper	3.5	--	--	--	--	1
	Iron	<10.0	--	--	--	--	1
	Lead	0.10	--	--	--	--	1
	Lithium	9.6	--	--	--	--	1
	Manganese	<0.10	--	--	--	--	1
	Molybdenum	0.30	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Coalmont Formation—Contiued	Nickel	0.68	--	--	--	--	1
	Selenium	0.50	--	--	--	--	1
	Strontium	117	--	--	--	--	1
	Vanadium	3.1	--	--	--	--	1
	Zinc	<1.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	2.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	2.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.10	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	2,130	--	--	--	--	1
	Uranium	0.18	--	--	--	--	1
Hanna aquifer	pH (standard units)	6.5	7.3	7.9	8.4	10.9	35
	Specific conductance (µS/cm)	67.0	1,140	2,020	3,280	6,200	36
	Hardness (as $CaCO_3$)	20.0	42.0	73.0	620	3,400	35
	Calcium	2.9	11.0	18.0	150	550	35
	Magnesium	0.50	4.0	8.8	53.0	480	35
	Sodium	3.7	41.0	340	640	1,100	35
	Potassium	0.40	3.2	6.3	9.5	26.0	33
	Sodium-adsorption ratio (unitless)	0.20	0.90	8.4	31.0	78.0	34
	Alkalinity (as $CaCO_3$)	29.0	170	364	770	1,360	35
	Chloride	0.20	4.9	10.0	29.0	180	35
	Fluoride	0.10	0.30	0.45	1.3	27.0	33
	Silica	0.30	5.6	9.0	14.0	21.0	35
	Sulfate	2.5	74.0	420	1,000	4,300	35
	Total dissolved solids	28.0	645	1,380	1,980	7,500	35
	Ammonia (as N)	1.4	--	--	--	--	1
	Ammonia+organic nitrogen, unfiltered (as N)	--	3.6	4.1	7.4	38.0	9
	Ammonia, unfiltered (as N)	--	2.3	2.7	6.4	34.0	9
	Nitrate+nitrite (as N)	<0.10	--	--	--	--	1
	Nitrate+nitrite, unfiltered (as N)	--	0.014	0.031	0.070	0.41	26
	Nitrate, unfiltered (as N)	--	0.010	0.020	0.050	0.36	10
	Nitrite, unfiltered (as N)	--	0.010	0.010	0.020	0.36	17
	Organic nitrogen, unfiltered (as N)	--	0.25	1.0	1.4	4.0	8
	Total nitrogen, unfiltered (as N)	--	3.6	4.2	7.4	38.0	9
	Phosphorus, unfiltered (as P)	--	0.040	0.16	1.1	11.0	26
	Organic carbon, unfiltered	--	12.0	22.0	50.0	62.0	7
	Aluminum	--	13.1	24.7	46.4	250	22
	Antimony	<1.0	--	--	--	2.0	2
	Arsenic	--	0.48	1.0	2.0	13.0	23

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hanna aquifer—Continued	Barium	--	19.9	29.7	44.3	130	5
	Boron	--	40.0	60.0	100	1,500	30
	Chromium	--	1.0	2.7	7.0	60.0	13
	Copper	--	1.6	2.5	6.5	20.0	16
	Iron	--	70.0	120	560	14,000	23
	Iron, unfiltered	--	1,800	5,050	13,000	130,000	26
	Lead	--	1.4	2.2	3.5	9.0	19
	Lithium	--	20.0	60.0	100	180	19
	Manganese	--	40.0	80.0	190	1,300	22
	Manganese, unfiltered	--	70.0	170	610	2,800	21
	Molybdenum	--	1.0	3.0	12.0	32.0	19
	Nickel	--	1.9	2.1	2.4	3.0	17
	Strontium	--	130	160	290	290	3
	Vanadium	--	0.20	0.58	1.7	25.0	11
	Zinc	--	10.9	20.0	58.0	870	21
	Gross beta radioactivity (picocuries per liter)	--	3.7	6.5	12.0	39.0	13
	Radium-226 (picocuries per liter)	--	0.16	0.22	0.35	0.84	13
	Uranium	--	0.65	1.9	8.5	14.0	4
Ferris aquifer	Dissolved oxygen	0.40	--	--	--	0.60	2
	pH (standard units)	6.7	7.1	7.2	7.8	8.7	30
	Specific conductance (µS/cm)	1,550	3,100	3,700	5,500	9,810	29
	Hardness (as $CaCO_3$)	29.0	690	1,000	1,900	5,200	33
	Calcium	5.7	78.0	180	270	540	33
	Magnesium	3.6	76.0	150	290	960	33
	Sodium	26.0	160	440	660	2,400	33
	Potassium	1.5	5.9	10.0	18.0	110	33
	Sodium-adsorption ratio (unitless)	0.20	1.8	5.8	13.0	44.0	33
	Alkalinity (as $CaCO_3$)	43.0	458	676	837	1,160	33
	Chloride	5.1	12.0	21.0	43.0	200	33
	Fluoride	0.10	0.20	0.30	0.50	3.1	33
	Silica	0.10	7.4	11.0	13.0	31.0	33
	Sulfate	28.0	870	1,400	2,400	5,200	33
	Total dissolved solids	614	1,930	2,770	4,410	8,240	33
	Ammonia (as N)	4.1	--	--	--	5.0	2
	Ammonia+organic nitrogen, unfiltered (as N)	--	1.4	4.3	5.7	16.0	15
	Ammonia, unfiltered (as N)	--	0.040	2.5	4.2	16.0	15
	Nitrate+nitrite, unfiltered (as N)	--	0.015	0.074	0.22	40.0	35
	Nitrate, unfiltered (as N)	--	0.025	0.075	1.0	40.0	16
	Nitrite (as N)	<0.010	--	--	--	<0.010	2
	Nitrite, unfiltered (as N)	--	0.010	0.010	0.035	0.40	20

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Ferris aquifer—Continued	Organic nitrogen, unfiltered (as N)	--	0.20	0.50	1.9	6.1	10
	Total nitrogen, unfiltered (as N)	--	1.7	4.7	6.4	32.0	15
	Orthophosphate (as P)	0.010	--	--	--	0.010	2
	Phosphorus (as P)	0.010	--	--	--	0.050	2
	Phosphorus, unfiltered (as P)	--	0.035	0.20	0.39	4.7	37
	Organic carbon	12.0	--	--	--	16.0	2
	Organic carbon, unfiltered	--	4.6	19.0	20.0	20.0	3
	Aluminum	--	11.5	21.0	38.6	190	28
	Antimony	<1.0	--	--	--	<1.0	2
	Arsenic	--	0.37	0.93	2.5	29.0	28
	Beryllium	--	4.3	6.6	10.0	20.0	26
	Boron	--	100	115	140	1,700	30
	Cadmium	--	0.92	1.3	1.9	5.0	17
	Chromium	--	2.4	5.6	20.0	40.0	18
	Copper	--	2.4	3.9	6.6	20.0	12
	Iron	--	70.0	360	2,600	26,000	30
	Iron, unfiltered	--	4,600	9,650	18,000	47,000	26
	Lead	--	2.3	3.7	5.8	22.0	24
	Lithium	--	40.0	60.0	120	1,000	22
	Manganese	--	55.0	140	375	4,800	28
	Manganese, unfiltered	--	160	310	530	2,000	26
	Molybdenum	--	0.53	1.5	5.0	24.0	26
	Nickel	--	2.0	4.0	8.0	51.0	22
	Selenium	--	0.011	0.089	0.71	80.0	26
	Strontium	--	540	6,500	10,000	10,000	3
	Vanadium	--	0.30	0.80	340	360	7
	Zinc	--	16.1	30.0	60.0	5,200	28
	Gross beta radioactivity (picocuries per liter)	--	7.9	11.5	16.9	29.0	8
	Radium-226 (picocuries per liter)	--	0.26	0.50	1.8	2.1	8
	Uranium	--	0.60	1.0	3.3	12.0	7
Medicine Bow aquifer	pH (standard units)	7.1	--	7.4	--	8.2	3
	Specific conductance (µS/cm)	239	--	560	--	1,640	3
	Hardness (as $CaCO_3$)	99.0	--	230	--	250	3
	Calcium	26.0	--	45.0	--	84.0	3
	Magnesium	8.0	--	28.0	--	34.0	3
	Sodium	7.4	--	33.0	--	274	3
	Potassium	1.6	--	1.8	--	3.6	3
	Sodium-adsorption ratio (unitless)	0.33	--	1.0	--	6.4	3
	Alkalinity (as $CaCO_3$)	95.1	--	188	--	220	3
	Chloride	1.2	--	4.4	--	16.0	3

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Medicine Bow aquifer—Continued	Fluoride	0.30	--	0.50	--	0.60	3
	Silica	6.1	--	8.8	--	11.0	3
	Sulfate	15.0	--	69.0	--	714	3
	Total dissolved solids	119	--	308	--	1,240	3
	Nitrate+nitrite, unfiltered (as N)	0.010	--	--	--	--	1
	Nitrate (as N)	0.068	--	--	--	0.52	2
	Nitrate, unfiltered (as N)	0.010	--	--	--	--	1
	Nitrite, unfiltered (as N)	<0.010	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.19	--	--	--	--	1
	Aluminum	20.0	--	--	--	--	1
	Arsenic	1.0	--	--	--	--	1
	Beryllium	<10.0	--	--	--	--	1
	Boron	--	20.0	40.0	110	110	3
	Copper	<2.0	--	--	--	--	1
	Iron	2,000	--	--	--	--	1
	Iron, unfiltered	100	--	--	--	40,000	2
	Lead	2.0	--	--	--	--	1
	Lithium	20.0	--	--	--	--	1
	Manganese	240	--	--	--	--	1
	Manganese, unfiltered	330	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Molybdenum	<1.0	--	--	--	--	1
	Nickel	<2.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Vanadium	0.20	--	--	--	--	1
	Zinc	6.0	--	--	--	--	1
Lewis confining unit	Dissolved oxygen	1.3	--	--	--	2.0	2
	pH (standard units)	7.3	7.4	7.7	8.0	8.0	4
	Specific conductance (µS/cm)	610	1,990	2,120	2,870	8,170	5
	Hardness (as $CaCO_3$)	98.0	329	655	2,850	4,950	4
	Calcium	21.0	83.5	155	290	416	4
	Magnesium	11.0	29.5	66.0	516	948	4
	Sodium	222	314	448	594	697	4
	Potassium	2.2	3.2	4.7	11.4	17.6	4
	Sodium-adsorption ratio (unitless)	3.5	3.9	6.7	13.5	18.0	4
	Alkalinity (as $CaCO_3$)	176	235	332	440	510	4
	Bromide	0.48	--	--	--	--	1
	Chloride	9.6	18.8	48.5	83.5	98.0	4
	Fluoride	0.30	0.55	0.87	2.2	3.4	4
	Silica	9.1	10.4	11.8	27.0	42.0	4
	Sulfate	595	818	1,110	3,390	5,590	4
	Total dissolved solids	1,340	1,570	1,990	5,680	9,180	4

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Lewis confining unit—Continued	Ammonia (as N)	0.080	--	--	--	0.12	2
	Nitrate+nitrite (as N)	<0.060	--	--	--	0.32	2
	Nitrate (as N)	--	0.040	0.10	0.52	2.3	5
	Nitrite (as N)	<0.008	--	--	--	<0.008	2
	Orthophosphate (as P)	<0.020	--	--	--	<0.020	2
	Aluminum	<3.0	--	--	--	--	1
	Antimony	0.16	--	--	--	--	1
	Arsenic	1.5	--	--	--	--	1
	Barium	5.0	--	--	--	--	1
	Beryllium	<0.20	--	--	--	--	1
	Boron	--	220	350	516	591	4
	Cadmium	<0.10	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.79	--	--	--	--	1
	Copper	19.1	--	--	--	--	1
	Iron	<50.0	--	--	--	--	1
	Iron, unfiltered	--	30.0	470	3,700	3,700	3
	Lead	<0.20	--	--	--	--	1
	Lithium	585	--	--	--	--	1
	Manganese	53.2	--	--	--	--	1
	Molybdenum	2.7	--	--	--	--	1
	Nickel	6.4	--	--	--	--	1
	Selenium	8.5	--	--	--	--	1
	Strontium	6,820	--	--	--	--	1
	Vanadium	3.3	--	--	--	--	1
	Zinc	10.9	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	450	--	--	--	--	1
	Uranium	42.7	--	--	--	--	1
Mesaverde aquifer	Dissolved oxygen	0.10	0.20	0.30	0.50	1.0	6
	pH (standard units)	6.1	6.9	7.3	7.7	8.2	12
	Specific conductance (µS/cm)	302	1,040	1,430	1,850	5,390	17
	Hardness (as $CaCO_3$)	25.0	240	440	617	2,200	17
	Calcium	5.8	52.0	104	152	417	17
	Magnesium	2.6	24.0	41.0	66.1	271	17
	Sodium	12.0	54.0	100	337	691	17
	Potassium	1.0	2.6	3.3	4.8	7.1	17
	Sodium-adsorption ratio (unitless)	0.30	0.83	1.8	7.0	29.0	17
	Alkalinity (as $CaCO_3$)	52.5	184	269	336	738	17
	Bromide	0.040	0.040	0.060	0.070	0.070	6
	Chloride	0.10	6.1	10.0	20.0	93.0	17
	Fluoride	0.11	0.46	0.51	0.60	3.2	17

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mesaverde aquifer—Continued	Silica	8.4	11.0	13.4	17.0	26.0	17
	Sulfate	5.0	253	375	703	3,430	17
	Total dissolved solids	181	724	974	1,440	5,200	17
	Ammonia (as N)	--	0.048	0.17	0.27	0.61	6
	Ammonia+organic nitrogen, unfiltered (as N)	0.47	--	--	--	--	1
	Ammonia, unfiltered (as N)	0.38	--	--	--	--	1
	Nitrate+nitrite, unfiltered (as N)	<0.10	--	--	--	--	1
	Nitrate (as N)	--	0.005	0.019	0.071	1.2	17
	Organic nitrogen, unfiltered (as N)	0.090	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.47	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.020	--	--	--	--	1
	Arsenic	--	0.16	0.26	0.42	0.80	7
	Barium	--	8.0	17.0	23.0	110	6
	Boron	--	60.0	100	170	390	17
	Cadmium	--	0.002	0.019	0.42	3.0	7
	Cobalt	--	0.22	0.40	0.67	1.1	6
	Copper	--	1.3	1.9	2.8	4.4	7
	Iron	--	32.0	1,510	4,760	5,140	7
	Iron, unfiltered	--	130	1,300	1,700	8,900	11
	Lead	--	0.12	0.49	1.4	3.0	7
	Lithium	--	16.9	32.9	84.9	87.0	7
	Manganese	--	23.8	27.0	382	600	7
	Manganese, unfiltered	610	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Molybdenum	--	0.26	0.47	1.5	1.5	7
	Nickel	--	0.93	2.2	2.4	4.0	7
	Selenium	--	0.35	0.47	0.63	0.80	7
	Strontium	--	962	1,330	1,510	4,910	6
	Vanadium	--	1.0	1.4	2.2	2.6	6
	Zinc	--	9.4	96.1	521	4,030	7
	Gross beta radioactivity (picocuries per liter)	7.3	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.55	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	180	700	1,260	1,490	6
	Uranium	--	0.33	0.97	3.5	6.2	7
Cody confining unit	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	6,020	--	--	--	--	1
	Hardness (as $CaCO_3$)	1,300	--	--	--	--	1
	Calcium	201	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cody confining unit—Continued	Magnesium	192	--	--	--	--	1
	Sodium	1,070	--	--	--	--	1
	Potassium	7.6	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	13.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	474	--	--	--	--	1
	Chloride	70.0	--	--	--	--	1
	Fluoride	2.0	--	--	--	--	1
	Silica	8.5	--	--	--	--	1
	Sulfate	3,080	--	--	--	--	1
	Total dissolved solids	5,110	--	--	--	--	1
	Nitrate (as N)	<0.023	--	--	--	--	1
	Iron, unfiltered	<10.0	--	--	--	--	1
Steele confining unit	Dissolved oxygen	0.10	--	4.2	--	4.9	3
	pH (standard units)	7.2	7.4	7.7	7.8	7.8	5
	Specific conductance (µS/cm)	302	1,080	4,010	6,090	18,000	8
	Hardness (as $CaCO_3$)	86.0	130	310	2,180	4,520	7
	Calcium	12.0	35.0	49.0	295	366	7
	Magnesium	11.0	12.0	45.0	348	873	7
	Sodium	8.8	45.0	1,040	1,220	3,500	7
	Potassium	1.0	2.0	4.1	10.8	13.2	7
	Sodium-adsorption ratio (unitless)	0.33	1.7	9.7	30.3	53.5	7
	Alkalinity (as $CaCO_3$)	150	175	351	748	899	7
	Bromide	0.030	--	0.22	--	3.6	3
	Chloride	0.98	11.0	29.5	470	659	7
	Fluoride	0.12	0.30	0.51	1.3	1.3	7
	Silica	6.0	7.9	9.6	13.1	16.0	7
	Sulfate	12.9	44.0	1,700	3,920	10,600	7
	Total dissolved solids	175	272	3,420	6,440	17,900	7
	Ammonia (as N)	--	0.63	1.6	3.6	5.1	4
	Nitrate+nitrite (as N)	--	0.040	0.10	5.6	11.0	4
	Nitrate (as N)	--	0.093	0.17	1.6	10.9	8
	Nitrite (as N)	--	0.008	0.019	0.066	0.10	4
	Antimony	--	0.040	0.080	37.8	37.8	3
	Arsenic	--	0.40	0.90	22.6	22.6	3
	Barium	--	4.0	70.0	121	121	3
	Boron	--	90.0	570	1,040	2,300	7
	Cobalt	--	0.068	0.54	55.5	55.5	3
	Copper	--	11.5	13.7	165	165	3
	Iron, unfiltered	--	110	520	6,700	6,700	3
	Lithium	--	7.1	606	3,200	3,200	3
	Manganese	--	10.5	261	15,600	15,600	3
	Molybdenum	--	0.50	1.8	222	222	3

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Steele confining unit—Continued	Strontium	--	329	6,410	13,300	13,300	3
	Vanadium	--	0.10	3.5	64.5	64.5	3
	Zinc	--	9.4	19.7	89.8	89.8	3
	Radon-222, unfiltered (picocuries per liter)	--	70.0	140	1,090	1,090	3
	Uranium	--	0.080	3.8	349	349	3
Niobrara confining unit	Dissolved oxygen	0.10	--	--	--	--	1
	pH (standard units)	7.0	--	7.5	--	8.0	3
	Specific conductance (µS/cm)	1,030	1,560	2,850	3,350	3,670	5
	Hardness (as $CaCO_3$)	170	240	447	892	1,200	4
	Calcium	43.0	59.5	97.0	198	278	4
	Magnesium	16.0	23.0	50.3	96.3	122	4
	Sodium	118	199	345	428	446	4
	Potassium	2.6	3.5	4.6	6.3	7.8	4
	Sodium-adsorption ratio (unitless)	2.9	4.0	6.6	8.6	9.2	4
	Alkalinity (as $CaCO_3$)	300	307	332	358	367	4
	Chloride	50.0	69.3	139	192	194	4
	Fluoride	0.36	0.58	0.85	0.90	0.90	4
	Silica	9.5	11.0	12.7	13.5	14.0	4
	Sulfate	133	159	657	1,280	1,420	4
	Total dissolved solids	679	816	1,510	2,510	2,950	4
	Ammonia (as N)	0.27	--	--	--	2.4	2
	Nitrate+nitrite (as N)	<0.060	--	--	--	0.58	2
	Nitrite (as N)	<0.008	--	--	--	<0.010	2
	Orthophosphate (as P)	<0.010	--	--	--	<0.020	2
	Boron	--	510	770	940	940	3
	Iron, unfiltered	40.0	--	--	--	50.0	2
	Radon-222, unfiltered (picocuries per liter)	410	--	--	--	--	1
Frontier aquifer	Specific conductance (µS/cm)	610	--	--	--	--	1
	Hardness (as $CaCO_3$)	18.0	--	--	--	--	1
	Calcium	4.4	--	--	--	--	1
	Magnesium	1.7	--	--	--	--	1
	Sodium	137	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	14.1	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	268	--	--	--	--	1
	Chloride	7.5	--	--	--	--	1
	Fluoride	1.6	--	--	--	--	1
	Silica	6.9	--	--	--	--	1
	Sulfate	36.0	--	--	--	--	1
	Total dissolved solids	358	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer—Continued	Nitrate (as N)	0.045	--	--	--	--	1
	Boron	600	--	--	--	--	1
Cloverly aquifer	pH (standard units)	7.3	7.6	8.1	9.4	9.5	7
	Specific conductance (µS/cm)	301	361	595	2,670	6,260	8
	Hardness (as $CaCO_3$)	2.0	5.8	25.0	66.0	470	8
	Calcium	1.0	1.5	5.0	17.0	126	7
	Magnesium	0.10	0.40	2.0	15.0	37.0	7
	Sodium	65.0	69.0	96.0	220	1,600	9
	Potassium	0.10	0.70	2.3	6.0	8.4	8
	Sodium-adsorption ratio (unitless)	7.7	15.5	41.0	55.0	68.0	5
	Alkalinity (as $CaCO_3$)	78.7	142	190	297	1,250	9
	Bromide	1.0	--	--	--	--	1
	Chloride	1.0	3.0	3.5	7.1	1,140	9
	Fluoride	0.50	0.72	1.1	2.1	4.2	8
	Silica	10.0	11.0	16.0	23.0	32.0	9
	Sulfate	1.5	24.0	30.0	85.0	1,090	9
	Total dissolved solids	188	219	282	557	4,480	9
	Nitrate+nitrite (as N)	<0.10	--	--	--	--	1
	Nitrite (as N)	<0.010	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	<4.0	--	--	--	<5.0	2
	Barium	23.0	--	--	--	<100	2
	Beryllium	5.0	--	--	--	--	1
	Boron	--	39.4	145	380	900	8
	Cadmium	<0.50	--	--	--	<10.0	2
	Chromium	<50.0	--	--	--	<50.0	2
	Copper	<10.0	--	--	--	<10.0	2
	Iron	90.0	--	--	--	320	2
	Iron, unfiltered	--	110	300	520	1,000	7
	Lead	<1.0	--	--	--	<50.0	2
	Manganese	<10.0	--	--	--	45.0	2
	Mercury	<0.50	--	--	--	0.60	2
	Nickel	<20.0	--	--	--	--	1
	Selenium	<4.0	--	--	--	<5.0	2
	Zinc	<10.0	--	--	--	10.0	2
	Gross alpha radioactivity (picocuries per liter)	1.8	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	1.1	--	--	--	3.3	2
	Radium-226 (picocuries per liter)	0.40	--	--	--	1.3	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	1.0	2
	Uranium	<0.30	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Sundance aquifer	pH (standard units)	8.5	--	--	--	8.6	2
	Specific conductance (µS/cm)	1,750	--	2,620	--	2,870	3
	Hardness (as $CaCO_3$)	5.0	--	6.0	--	590	3
	Calcium	1.0	--	2.0	--	156	3
	Magnesium	0.10	--	0.90	--	49.0	3
	Sodium	378	--	460	--	746	3
	Potassium	1.6	--	4.2	--	5.7	3
	Sodium-adsorption ratio (unitless)	6.8	--	90.0	--	130	3
	Alkalinity (as $CaCO_3$)	64.8	--	934	--	971	3
	Chloride	26.0	--	39.0	--	187	3
	Fluoride	1.0	--	--	--	6.8	2
	Silica	7.4	--	11.0	--	30.0	3
	Sulfate	1.0	--	302	--	1,280	3
	Total dissolved solids	1,100	--	1,910	--	2,010	3
	Boron	--	180	450	3,600	3,600	3
	Iron, unfiltered	--	30.0	170	4,200	4,200	3
Nugget aquifer	pH (standard units)	8.7	8.8	8.8	8.9	8.9	4
	Specific conductance (µS/cm)	923	962	1,030	1,055	1,060	4
	Hardness (as $CaCO_3$)	9.0	9.0	9.0	16.5	24.0	4
	Calcium	2.0	2.0	2.0	3.0	4.0	4
	Magnesium	1.0	1.0	1.0	2.0	3.0	4
	Sodium	249	252	257	267	273	4
	Potassium	2.0	--	2.0	--	2.0	3
	Alkalinity (as $CaCO_3$)	360	375	400	415	420	4
	Chloride	3.0	4.5	6.5	7.5	8.0	4
	Fluoride	0.80	0.90	1.1	1.4	1.6	4
	Silica	1.5	--	9.8	--	11.9	3
	Sulfate	160	160	162	167	170	4
	Total dissolved solids	596	622	673	806	913	4
	Boron	--	300	400	400	400	3
	Molybdenum	20.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	10.0	--	--	--	10.8	2
	Uranium	<1.0	--	--	--	10.0	2
Chugwater aquifer and confining unit	Specific conductance (µS/cm)	708	--	--	--	--	1
	Hardness (as $CaCO_3$)	230	--	--	--	--	1
	Calcium	53.0	--	--	--	--	1
	Magnesium	25.0	--	--	--	--	1
	Sodium	56.0	--	--	--	--	1
	Potassium	3.6	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	1.6	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	163	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater aquifer and confining unit—Continued	Chloride	9.9	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	175	--	--	--	--	1
	Total dissolved solids	442	--	--	--	--	1
	Nitrate (as N)	1.7	--	--	--	--	1
	Boron	140	--	--	--	--	1
Satanka confining unit	Specific conductance (µS/cm)	1,780	--	--	--	--	1
	Hardness (as $CaCO_3$)	900	--	--	--	--	1
	Calcium	148	--	--	--	--	1
	Magnesium	128	--	--	--	--	1
	Sodium	110	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	384	--	--	--	--	1
	Chloride	23.0	--	--	--	--	1
	Fluoride	1.5	--	--	--	--	1
	Sulfate	667	--	--	--	--	1
	Total dissolved solids	1,330	--	--	--	--	1
	Nitrate (as N)	0.045	--	--	--	--	1
	Boron	180	--	--	--	--	1
Casper aquifer	pH (standard units)	7.0	--	7.5	--	7.7	3
	Specific conductance (µS/cm)	589	--	3,780	--	13,800	3
	Hardness (as $CaCO_3$)	205	--	1,100	--	1,800	3
	Calcium	45.0	--	378	--	630	3
	Magnesium	22.0	--	43.0	--	43.0	3
	Sodium	32.0	--	448	--	2,740	3
	Potassium	1.9	--	16.6	--	75.0	3
	Sodium-adsorption ratio (unitless)	5.8	--	--	--	28.5	2
	Alkalinity (as $CaCO_3$)	96.7	--	149	--	166	3
	Chloride	50.0	--	350	--	3,720	3
	Fluoride	0.30	--	2.9	--	3.9	3
	Silica	16.0	--	26.0	--	37.0	3
	Sulfate	35.0	--	1,590	--	2,160	3
	Total dissolved solids	340	--	3,060	--	9,650	3
	Nitrate (as N)	0.023	--	--	--	0.25	2
	Boron	--	100	360	650	650	3
	Iron	10.0	--	--	--	--	1
	Iron, unfiltered	1,300	--	--	--	--	1
Tensleep aquifer	pH (standard units)	8.0	--	--	--	--	1
	Specific conductance (µS/cm)	499	--	--	--	--	1
	Hardness (as $CaCO_3$)	200	--	--	--	270	2
	Calcium	48.0	--	--	--	60.0	2
	Magnesium	20.0	--	--	--	29.0	2

Appendix E2. Summary statistics for environmental water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Tensleep aquifer—Continued	Sodium	21.0	--	--	--	180	2
	Potassium	3.8	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.64	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	161	--	--	--	180	2
	Chloride	17.0	--	--	--	58.0	2
	Fluoride	0.60	--	--	--	2.7	2
	Silica	9.2	--	--	--	--	1
	Sulfate	60.0	--	--	--	460	2
	Total dissolved solids	276	--	--	--	950	2
	Nitrate (as N)	0.023	--	--	--	0.050	2
	Arsenic	13.0	--	--	--	--	1
	Barium	1.0	--	--	--	--	1
	Boron	80.0	--	--	--	--	1
	Copper	70.0	--	--	--	--	1
	Iron	600	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
	Manganese	10.0	--	--	--	--	1
	Zinc	160	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	17.0	--	--	--	--	1
Precambrian basal confining unit	pH (standard units)	7.1	--	--	--	7.1	2
	Specific conductance (µS/cm)	244	--	--	--	280	2
	Hardness (as $CaCO_3$)	84.7	--	--	--	--	1
	Calcium	26.0	--	--	--	--	1
	Magnesium	4.8	--	--	--	--	1
	Sodium	17.0	--	--	--	--	1
	Potassium	3.3	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.80	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	113	--	--	--	--	1
	Chloride	9.2	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	38.0	--	--	--	--	1
	Sulfate	13.0	--	--	--	--	1
	Total dissolved solids	181	--	--	--	--	1
	Nitrate+nitrite (as N)	0.30	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.020	--	--	--	--	1

Appendix E3. Summary statistics for environmental water samples, Sierra Madre, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer	pH (standard units)	9.3	--	--	--	--	1
	Specific conductance (µS/cm)	1,170	--	--	--	--	1
	Hardness (as $CaCO_3$)	19.0	--	--	--	--	1
	Calcium	5.5	--	--	--	--	1
	Magnesium	1.3	--	--	--	--	1
	Sodium	290	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	29.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	604	--	--	--	--	1
	Chloride	6.5	--	--	--	--	1
	Fluoride	1.2	--	--	--	--	1
	Silica	7.8	--	--	--	--	1
	Sulfate	37.0	--	--	--	--	1
	Total dissolved solids	714	--	--	--	--	1
	Nitrate (as N)	<0.010	--	--	--	--	1
	Boron	370	--	--	--	--	1
	Iron, unfiltered	690	--	--	--	--	1
Precambrian basal confining unit	Dissolved oxygen	7.2	--	--	--	--	1
	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	311	--	--	--	--	1
	Hardness (as $CaCO_3$)	117	--	--	--	--	1
	Calcium	37.1	--	--	--	--	1
	Magnesium	5.9	--	--	--	--	1
	Sodium	18.7	--	--	--	--	1
	Potassium	1.6	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.75	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	139	--	--	--	--	1
	Bromide	0.090	--	--	--	--	1
	Chloride	5.7	--	--	--	--	1
	Fluoride	1.8	--	--	--	--	1
	Silica	20.0	--	--	--	--	1
	Sulfate	10.6	--	--	--	--	1
	Total dissolved solids	186	--	--	--	--	1
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	0.90	--	--	--	--	1
	Nitrate (as N)	<0.90	--	--	--	--	1
	Nitrite (as N)	<0.008	--	--	--	--	1
	Orthophosphate (as P)	0.010	--	--	--	--	1
	Aluminum	<1.0	--	--	--	--	1
	Antimony	0.04	--	--	--	--	1

Appendix E3. Summary statistics for environmental water samples, Sierra Madre, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Precambrian basal confining unit—Continued	Arsenic	13.0	--	--	--	--	1
	Barium	11.0	--	--	--	--	1
	Beryllium	<0.06	--	--	--	--	1
	Boron	35.0	--	--	--	--	1
	Cadmium	<0.04	--	--	--	--	1
	Chromium	<0.80	--	--	--	--	1
	Cobalt	0.08	--	--	--	--	1
	Copper	0.40	--	--	--	--	1
	Iron	<10.0	--	--	--	--	1
	Lead	<0.08	--	--	--	--	1
	Lithium	55.9	--	--	--	--	1
	Manganese	<0.10	--	--	--	--	1
	Molybdenum	2.0	--	--	--	--	1
	Nickel	<0.06	--	--	--	--	1
	Selenium	1.0	--	--	--	--	1
	Strontium	383	--	--	--	--	1
	Vanadium	2.4	--	--	--	--	1
	Zinc	1.8	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	45.9	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	11.0	--	--	--	--	1
	Radium-228 (picocuries per liter)	2.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	4,120	--	--	--	--	1
	Tritium, unfiltered (picocuries per liter)	2.9	--	--	--	--	1
	Uranium	12.8	--	--	--	--	1

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Specific conductance (µS/cm)	261	--	--	--	--	1
	Hardness (as $CaCO_3$)	130	--	--	--	--	1
	Calcium	38.0	--	--	--	--	1
	Magnesium	7.5	--	--	--	--	1
	Sodium	6.2	--	--	--	--	1
	Potassium	1.9	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.24	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	136	--	--	--	--	1
	Chloride	3.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	16.0	--	--	--	--	1
	Sulfate	6.0	--	--	--	--	1
	Total dissolved solids	161	--	--	--	--	1
	Nitrate (as N)	0.023	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
Aquifers in Quaternary glacial deposits	Specific conductance (µS/cm)	57.0	--	--	--	--	1
	Hardness (as $CaCO_3$)	22.0	--	--	--	--	1
	Calcium	8.4	--	--	--	--	1
	Magnesium	0.20	--	--	--	--	1
	Sodium	0.50	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.050	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	22.1	--	--	--	--	1
	Chloride	0.70	--	--	--	--	1
	Silica	3.6	--	--	--	--	1
	Sulfate	0.40	--	--	--	--	1
	Total dissolved solids	44.0	--	--	--	--	1
	Nitrate (as N)	0.25	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
	Iron, unfiltered	260	--	--	--	--	1
Browns Park aquifer	Dissolved oxygen	8.8	--	--	--	--	1
	pH (standard units)	6.1	7.0	8.0	8.1	8.4	6
	Specific conductance (µS/cm)	77.0	144	186	192	364	6
	Hardness (as $CaCO_3$)	32.8	--	--	--	45.7	2
	Calcium	9.6	15.0	20.5	30.0	69.0	6
	Magnesium	1.4	2.1	3.9	4.2	5.0	6
	Sodium	2.2	4.3	5.7	7.7	10.0	6
	Potassium	0.47	0.50	1.2	1.7	1.8	6
	Sodium-adsorption ratio (unitless)	0.16	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	37.0	64.0	80.8	100	190	6
	Bromide	0.030	--	--	--	--	1

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Browns Park aquifer—Continued	Chloride	0.10	0.43	1.0	1.2	3.0	6
	Fluoride	0.10	--	--	--	0.22	2
	Silica	9.5	--	--	--	14.1	2
	Sulfate	1.8	3.0	3.0	4.3	9.9	6
	Total dissolved solids	45.0	100	115	125	220	6
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	0.17	--	--	--	--	1
	Nitrite (as N)	<0.008	--	--	--	<0.10	2
	Orthophosphate (as P)	<0.020	--	--	--	--	1
	Aluminum	2.0	--	--	--	--	1
	Antimony	<0.05	--	--	--	3.0	2
	Arsenic	0.10	--	--	--	3.0	2
	Barium	22.0	--	--	--	<100	2
	Beryllium	<0.06	--	--	--	1.0	2
	Cadmium	0.04	--	--	--	<0.50	2
	Chromium	0.80	--	--	--	<50.0	2
	Cobalt	0.04	--	--	--	--	1
	Copper	1.7	--	--	--	4,280	2
	Iron	<10.0	--	--	--	1,340	2
	Lead	0.29	--	--	--	200	2
	Lithium	0.30	--	--	--	--	1
	Manganese	0.20	--	--	--	30.0	2
	Mercury	<0.20	--	--	--	--	1
	Molybdenum	<0.20	--	--	--	--	1
	Nickel	0.74	--	--	--	80.0	2
	Selenium	<0.30	--	--	--	<1.0	2
	Strontium	35.3	--	--	--	--	1
	Vanadium	0.70	--	--	--	--	1
	Zinc	49.2	--	--	--	130	2
	Gross alpha radioactivity (picocuries per liter)	<1.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	<1.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	1,030	--	--	--	--	1
	Uranium	0.05	--	--	--	10.0	2
Frontier aquifer	pH (standard units)	6.8	--	--	--	--	1
	Specific conductance (µS/cm)	332	--	--	--	--	1
	Hardness (as $CaCO_3$)	121	--	--	--	--	1
	Calcium	28.0	--	--	--	--	1
	Magnesium	12.3	--	--	--	--	1

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer—Continued	Sodium	17.1	--	--	--	--	1
	Potassium	1.7	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.68	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	87.0	--	--	--	--	1
	Chloride	9.3	--	--	--	--	1
	Fluoride	0.53	--	--	--	--	1
	Silica	10.2	--	--	--	--	1
	Sulfate	48.5	--	--	--	--	1
	Total dissolved solids	192	--	--	--	--	1
	Ammonia (as N)	0.030	--	--	--	--	1
	Nitrate+nitrite (as N)	2.8	--	--	--	--	1
	Nitrate (as N)	2.8	--	--	--	--	1
	Nitrite (as N)	0.014	--	--	--	--	1
	Orthophosphate (as P)	<0.010	--	--	--	--	1
Cloverly aquifer	pH (standard units)	7.7	--	--	--	8.1	2
	Specific conductance (µS/cm)	158	--	251	--	279	3
	Hardness (as $CaCO_3$)	94.4	--	--	--	120	2
	Calcium	24.8	--	38.0	--	42.0	3
	Magnesium	2.3	--	5.1	--	8.2	3
	Sodium	2.2	--	6.0	--	7.3	3
	Potassium	1.1	--	--	--	1.4	2
	Sodium-adsorption ratio (unitless)	0.24	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	91.0	--	121	--	170	3
	Chloride	0.90	--	1.3	--	2.0	3
	Fluoride	0.40	--	--	--	--	1
	Silica	26.0	--	--	--	--	1
	Sulfate	7.3	--	7.4	--	10.0	3
	Total dissolved solids	112	--	168	--	168	3
	Nitrate (as N)	0.023	--	--	--	0.15	2
	Boron	10.0	--	--	--	--	1
	Iron	<60.0	--	--	--	--	1
	Iron, unfiltered	90.0	--	--	--	--	1
Jelm aquifer	pH (standard units)	8.4	--	--	--	--	1
	Specific conductance (µS/cm)	713	--	--	--	--	1
	Calcium	94.0	--	--	--	--	1
	Magnesium	37.0	--	--	--	--	1
	Sodium	11.0	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	240	--	--	--	--	1
	Chloride	1.6	--	--	--	--	1
	Sulfate	200	--	--	--	--	1
	Total dissolved solids	492	--	--	--	--	1

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater confining unit	Specific conductance (µS/cm)	448	--	--	--	--	1
	Hardness (as $CaCO_3$)	230	--	--	--	--	1
	Calcium	59.0	--	--	--	--	1
	Magnesium	20.0	--	--	--	--	1
	Sodium	7.1	--	--	--	--	1
	Potassium	1.3	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.20	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	154	--	--	--	--	1
	Chloride	1.5	--	--	--	--	1
	Fluoride	1.1	--	--	--	--	1
	Silica	14.0	--	--	--	--	1
	Sulfate	82.0	--	--	--	--	1
	Total dissolved solids	314	--	--	--	--	1
	Nitrate (as N)	0.023	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
Casper aquifer (Casper Formation)	pH (standard units)	7.6	--	--	--	8.1	2
	Specific conductance (µS/cm)	350	--	--	--	361	2
	Hardness (as $CaCO_3$)	178	--	--	--	191	2
	Calcium	61.0	--	--	--	65.0	2
	Magnesium	6.2	--	--	--	7.0	2
	Sodium	3.0	--	--	--	4.5	2
	Potassium	1.8	--	--	--	3.0	2
	Alkalinity (as $CaCO_3$)	166	--	--	--	175	2
	Chloride	2.1	--	--	--	3.0	2
	Fluoride	0.47	--	--	--	0.59	2
	Silica	4.4	--	--	--	10.0	2
	Sulfate	15.1	--	--	--	19.0	2
	Total dissolved solids	191	--	--	--	256	2
	Nitrate (as N)	0.29	--	--	--	0.44	2
	Arsenic	5.2	--	--	--	7.0	2
	Barium	<100	--	--	--	<100	2
	Boron	<100	--	--	--	290	2
	Cadmium	<10.0	--	--	--	<10.0	2
	Chromium	<50.0	--	--	--	<50.0	2
	Copper	<10.0	--	--	--	<10.0	2
	Iron	<50.0	--	--	--	<50.0	2
	Lead	<5.0	--	--	--	<50.0	2
	Manganese, unfiltered	<10.0	--	--	--	10.0	2
	Mercury	<0.40	--	--	--	<1.0	2
	Selenium	<1.0	--	--	--	1.5	2
	Zinc	<10.0	--	--	--	170	2

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer (Casper Formation)—Continued	Gross alpha radioactivity (picocuries per liter)	<1.0	--	--	--	3.5	2
	Gross beta radioactivity (picocuries per liter)	2.7	--	--	--	3.9	2
	Radium-226 (picocuries per liter)	<0.20	--	--	--	0.40	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	1.4	2
	Uranium	6.7	--	--	--	--	1
Casper aquifer (Fountain Formation)	pH (standard units)	8.1	--	--	--	--	1
	Specific conductance (µS/cm)	402	--	--	--	--	1
	Calcium	75.0	--	--	--	--	1
	Magnesium	6.0	--	--	--	--	1
	Sodium	6.8	--	--	--	--	1
	Potassium	2.6	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	250	--	--	--	--	1
	Chloride	1.1	--	--	--	--	1
	Sulfate	7.3	--	--	--	--	1
	Total dissolved solids	236	--	--	--	--	1
Precambrian basal confining unit	pH (standard units)	6.4	--	7.8	--	8.2	3
	Specific conductance (µS/cm)	77.0	140	155	166	180	5
	Hardness (as $CaCO_3$)	28.0	48.8	78.3	91.0	95.0	4
	Calcium	7.8	17.6	20.0	23.9	28.0	5
	Magnesium	2.1	2.5	3.8	3.8	6.1	5
	Sodium	3.5	3.7	3.9	5.1	6.8	5
	Potassium	0.80	0.90	1.0	1.0	2.0	5
	Sodium-adsorption ratio (unitless)	0.17	--	--	--	0.30	2
	Alkalinity (as $CaCO_3$)	33.6	64.2	75.5	81.0	91.8	5
	Chloride	0.40	0.70	0.90	1.0	1.9	5
	Fluoride	0.10	0.10	0.14	0.17	0.17	4
	Silica	12.0	14.0	18.1	23.2	26.2	4
	Sulfate	1.9	3.1	3.3	3.4	4.6	5
	Total dissolved solids	55.0	96.0	96.0	100	111	5
	Nitrate (as N)	--	0.034	0.073	0.13	0.15	4
	Nitrite (as N)	<0.010	--	--	--	<0.10	2
	Antimony	<1.0	--	--	--	<5.0	2
	Arsenic	<1.0	--	--	--	<1.0	2
	Barium	<100	--	--	--	<100	2
	Beryllium	<0.50	--	--	--	<10.0	2
	Cadmium	<0.50	--	--	--	<10.0	2
	Chromium	<50.0	--	--	--	<50.0	2
	Copper	<1.0	--	--	--	<1.0	2
	Iron	<50.0	--	--	--	80.0	2

Appendix E4. Summary statistics for environmental water samples, Medicine Bow Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Precambrian basal confining unit—Continued	Iron, unfiltered	30.0	--	--	--	600	2
	Lead	<1.0	--	--	--	<50.0	2
	Manganese	<10.0	--	--	--	<10.0	2
	Mercury	<0.20	--	--	--	<1.0	2
	Nickel	<20.0	--	--	--	<50.0	2
	Selenium	<1.0	--	--	--	7.0	2
	Zinc	<10.0	--	--	--	20.0	2
	Gross alpha radioactivity (picocuries per liter)	4.4	--	--	--	5.3	2
	Gross beta radioactivity (picocuries per liter)	<1.0	--	--	--	4.0	2
	Radium-226 (picocuries per liter)	<0.20	--	--	--	<0.20	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	2.0	2
	Uranium	<0.30	--	--	--	1.0	2

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Dissolved oxygen	0.10	0.25	0.95	2.8	4.0	4
	pH (standard units)	6.5	7.1	7.2	7.3	7.7	5
	Specific conductance (µS/cm)	888	916	1,210	2,480	4,990	9
	Hardness (as $CaCO_3$)	370	385	410	450	480	4
	Calcium	82.0	90.5	110	129	136	4
	Magnesium	30.0	30.5	32.0	41.0	49.0	4
	Sodium	11.0	30.0	54.0	61.5	64.0	4
	Potassium	1.8	2.1	2.6	3.3	3.7	4
	Sodium-adsorption ratio (unitless)	0.22	0.63	1.2	1.4	1.4	4
	Alkalinity (as $CaCO_3$)	155	198	260	330	380	4
	Chloride	4.0	8.0	12.0	16.5	21.0	4
	Fluoride	0.60	0.70	0.85	1.2	1.5	4
	Silica	13.0	14.0	17.5	25.0	30.0	4
	Sulfate	86.0	143	236	306	340	4
	Total dissolved solids	578	614	664	666	928	5
	Nitrate+nitrite (as N)	--	0.36	3.6	8.2	9.9	4
	Nitrate (as N)	--	0.036	0.17	0.81	6.6	8
	Boron	--	80.0	105	155	190	4
	Iron, unfiltered	--	26.8	50.0	70.0	80.0	4
Cody confining unit	Dissolved oxygen	0.40	--	--	--	--	1
	pH (standard units)	7.4	--	--	--	--	1
	Specific conductance (µS/cm)	7,200	--	--	--	--	1
	Hardness (as $CaCO_3$)	2,960	--	--	--	--	1
	Calcium	410	--	--	--	--	1
	Magnesium	470	--	--	--	--	1
	Sodium	1,100	--	--	--	--	1
	Potassium	12.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	8.8	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	747	--	--	--	--	1
	Chloride	130	--	--	--	--	1
	Sulfate	4,800	--	--	--	--	1
	Total dissolved solids	7,760	--	--	--	--	1
	Nitrate+nitrite (as N)	4.5	--	--	--	--	1
	Arsenic	11.0	--	--	--	--	1
	Boron	1,700	--	--	--	--	1
	Cadmium	<1.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Molybdenum	17.0	--	--	--	--	1
	Selenium	51.0	--	--	--	--	1

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cody confining unit—Continued	Vanadium	2.0	--	--	--	--	1
	Zinc	20.0	--	--	--	--	1
	Tritium, unfiltered (picocuries per liter)	75.0	--	--	--	--	1
Frontier aquifer	Dissolved oxygen	3.0	--	--	--	--	1
	pH (standard units)	7.5	7.7	7.9	8.2	8.5	4
	Specific conductance (µS/cm)	972	4,100	5,220	11,500	14,000	5
	Hardness (as $CaCO_3$)	250	980	2,670	7,690	8,100	6
	Calcium	58.0	200	394	440	440	6
	Magnesium	25.0	110	408	1,600	1,700	6
	Sodium	118	210	1,090	2,120	8,500	6
	Potassium	2.4	7.7	27.0	37.0	37.0	5
	Sodium-adsorption ratio (unitless)	1.8	3.3	8.3	17.8	42.2	6
	Alkalinity (as $CaCO_3$)	164	178	316	745	832	6
	Bromide	1.6	--	--	--	--	1
	Chloride	24.0	54.0	88.5	121	770	6
	Fluoride	0.40	0.60	0.80	4.1	12.0	5
	Silica	6.3	10.7	18.0	21.5	22.0	4
	Sulfate	293	2,000	4,600	12,000	26,000	6
	Total dissolved solids	646	3,270	10,800	16,400	37,800	5
	Nitrate+nitrite (as N)	16.0	--	--	--	--	1
	Nitrate (as N)	--	0.72	0.81	3.3	5.3	5
	Orthophosphate (as P)	<0.010	--	--	--	<1.6	2
	Arsenic	2.0	--	--	--	--	1
	Barium	75.0	--	--	--	600	2
	Beryllium	<20.0	--	--	--	<20.0	2
	Boron	--	880	1,700	1,900	2,890	5
	Cobalt	<120	--	--	--	<120	2
	Iron	<120	--	--	--	<120	2
	Iron, unfiltered	--	30.0	60.0	310	310	3
	Lithium	160	--	--	--	410	2
	Manganese	<40.0	--	--	--	<40.0	2
	Nickel	<400	--	--	--	<400	2
	Selenium	--	55.5	168	1,230	2,200	4
	Strontium	3,000	--	--	--	7,400	2
	Zinc	--	30.0	260	340	340	3
	Tritium, unfiltered (picocuries per liter)	43.0	--	--	--	150	2
Mowry-Thermopolis confining unit (Mowry Shale)	Hardness (as $CaCO_3$)	750	--	--	--	--	1
	Calcium	204	--	--	--	--	1
	Magnesium	58.0	--	--	--	--	1
	Sodium	103	--	--	--	--	1

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mowry-Thermopolis confining unit (Mowry Shale)—Continued	Potassium	9.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	1.6	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	174	--	--	--	--	1
	Chloride	56.0	--	--	--	--	1
	Fluoride	0.60	--	--	--	--	1
	Silica	14.0	--	--	--	--	1
	Sulfate	680	--	--	--	--	1
	Total dissolved solids	1,320	--	--	--	--	1
	Orthophosphate (as P)	0.026	--	--	--	--	1
	Boron	780	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	8.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	17.0	--	--	--	--	1
	Uranium	4.7	--	--	--	--	1
Muddy Sandstone aquifer	pH (standard units)	6.8	--	--	--	--	1
	Calcium	18.9	--	--	--	--	1
	Magnesium	3.8	--	--	--	--	1
	Sodium	5.1	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	75.0	--	--	--	--	1
	Chloride	1.1	--	--	--	--	1
	Fluoride	0.050	--	--	--	--	1
	Silica	6.8	--	--	--	--	1
	Sulfate	8.0	--	--	--	--	1
	Total dissolved solids	76.0	--	--	--	--	1
Cloverly aquifer	pH (standard units)	6.5	7.9	8.0	8.6	8.9	12
	Specific conductance (µS/cm)	445	500	1,180	1,510	2,970	11
	Hardness (as $CaCO_3$)	14.0	--	28.0	--	130	3
	Calcium	1.0	3.0	24.0	62.1	75.3	13
	Magnesium	0.10	0.70	16.4	18.0	31.4	13
	Sodium	5.8	15.7	50.0	331	680	13
	Potassium	1.0	1.0	1.9	3.3	6.9	13
	Sodium-adsorption ratio (unitless)	1.9	--	33.6	--	79.4	3
	Alkalinity (as $CaCO_3$)	109	237	271	478	539	12
	Chloride	0.60	4.9	8.0	13.7	64.0	13
	Fluoride	0.27	0.41	0.60	1.8	2.1	13
	Silica	1.2	5.1	6.3	12.4	16.3	13
	Sulfate	13.0	72.2	143	236	1,310	13
	Total dissolved solids	228	310	419	884	2,090	13
	Nitrate (as N)	--	0.023	0.27	0.32	0.32	3
	Boron	--	100	330	480	480	3

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
	Iron, unfiltered	--	26.8	50.0	220	400	7
Morrison aquifer and confining unit	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	1,530	--	--	--	--	1
	Hardness (as $CaCO_3$)	310	--	--	--	--	1
	Calcium	45.0	--	--	--	--	1
	Magnesium	49.0	--	--	--	--	1
	Sodium	224	--	--	--	--	1
	Potassium	3.8	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	5.5	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	193	--	--	--	--	1
	Chloride	25.0	--	--	--	--	1
	Fluoride	1.2	--	--	--	--	1
	Silica	7.8	--	--	--	--	1
	Sulfate	555	--	--	--	--	1
	Total dissolved solids	1,030	--	--	--	--	1
	Nitrate (as N)	0.045	--	--	--	--	1
	Boron	310	--	--	--	--	1
	Iron, unfiltered	1,100	--	--	--	--	1
Sundance aquifer	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	345	--	--	--	905	2
	Hardness (as $CaCO_3$)	170	--	--	--	--	1
	Calcium	9.3	--	--	--	29.0	2
	Magnesium	2.8	--	--	--	24.0	2
	Sodium	8.0	--	--	--	195	2
	Potassium	1.3	--	--	--	2.2	2
	Sodium-adsorption ratio (unitless)	0.27	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	148	--	--	--	204	2
	Chloride	2.2	--	--	--	5.5	2
	Fluoride	0.23	--	--	--	0.30	2
	Silica	4.2	--	--	--	9.1	2
	Sulfate	31.0	--	--	--	287	2
	Total dissolved solids	200	--	--	--	604	2
	Nitrate (as N)	1.7	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
Chugwater confining unit	pH (standard units)	6.3	7.2	7.5	7.7	7.8	11
	Specific conductance (µS/cm)	713	1,240	1,790	2,240	2,950	17
	Hardness (as $CaCO_3$)	260	430	1,000	1,100	1,400	9
	Calcium	46.0	194	265	476	606	18
	Magnesium	29.0	69.8	92.5	106	155	18
	Sodium	4.4	15.0	25.0	63.0	148	18
	Potassium	1.1	2.0	3.1	4.0	9.9	14

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater confining unit—Continued	Sodium-adsorption ratio (unitless)	0.10	0.20	0.58	1.8	3.4	7
	Alkalinity (as $CaCO_3$)	107	124	163	228	392	18
	Chloride	3.2	5.2	12.0	30.0	88.7	18
	Fluoride	0.10	0.31	0.50	0.80	2.6	14
	Silica	5.9	16.0	19.4	23.0	34.4	14
	Sulfate	220	620	939	1,420	1,890	18
	Total dissolved solids	456	1,030	1,550	2,090	2,890	18
	Ammonia (as N)	<0.010	--	--	--	--	1
	Ammonia+organic nitrogen, unfiltered (as N)	0.16	--	--	--	--	1
	Ammonia, unfiltered (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	3.0	--	--	--	--	1
	Nitrate+nitrite, unfiltered (as N)	1.5	--	--	--	--	1
	Nitrate (as N)	--	0.24	0.61	1.6	2.5	8
	Nitrite (as N)	<0.010	--	--	--	--	1
	Organic nitrogen, unfiltered (as N)	0.16	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	1.7	--	--	--	--	1
	Orthophosphate (as P)	<0.010	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.010	--	--	--	--	1
	Aluminum	40.0	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	2.0	--	--	--	--	1
	Beryllium	<10.0	--	--	--	--	1
	Boron	--	85.0	120	220	350	8
	Chromium	<20.0	--	--	--	--	1
	Copper	2.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
	Lead	2.0	--	--	--	--	1
	Lithium	20.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Manganese, unfiltered	<10.0	--	--	--	--	1
	Mercury	<0.50	--	--	--	--	1
	Molybdenum	4.0	--	--	--	--	1
	Selenium	4.0	--	--	--	--	1
	Vanadium	8.0	--	--	--	--	1
	Zinc	220	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	2,490	--	--	--	--	1
Chugwater confining unit (Alcova Limestone)	pH (standard units)	7.8	--	--	--	8.0	2
	Specific conductance (µS/cm)	944	--	--	--	963	2
	Calcium	68.0	--	--	--	71.0	2
	Magnesium	60.1	--	--	--	61.0	2

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater confining unit (Alcova Limestone)—Continued	Sodium	45.0	--	--	--	49.0	2
	Potassium	5.6	--	--	--	5.7	2
	Alkalinity (as $CaCO_3$)	244	--	--	--	264	2
	Chloride	2.6	--	--	--	4.1	2
	Fluoride	0.45	--	--	--	0.45	2
	Silica	16.0	--	--	--	16.7	2
	Sulfate	242	--	--	--	279	2
	Total dissolved solids	628	--	--	--	648	2
	Iron, unfiltered	<50.0	--	--	--	<50.0	2
Goose Egg confining unit	pH (standard units)	7.3	7.4	7.6	7.8	7.9	12
	Specific conductance (µS/cm)	1,300	2,530	2,770	3,070	3,400	12
	Calcium	237	486	521	566	620	12
	Magnesium	29.5	97.3	117	213	236	12
	Sodium	3.0	22.1	49.5	71.4	268	12
	Potassium	0.50	2.8	5.3	6.6	9.9	12
	Alkalinity (as $CaCO_3$)	110	151	174	203	218	12
	Chloride	0.60	4.1	16.3	19.6	51.3	12
	Fluoride	0.26	0.50	0.61	1.0	1.8	12
	Silica	3.6	4.9	6.2	14.1	18.8	12
	Sulfate	592	1,550	1,740	2,010	2,220	12
	Total dissolved solids	1,030	2,400	2,650	2,910	3,220	12
Satanka confining unit	pH (standard units)	7.2	7.3	7.3	7.5	7.7	4
	Specific conductance (µS/cm)	361	410	1,190	1,260	2,550	10
	Hardness (as $CaCO_3$)	150	211	605	751	1,800	10
	Calcium	34.0	55.3	177	190	555	11
	Magnesium	15.0	19.0	49.0	71.0	100	11
	Sodium	2.7	9.0	12.2	29.0	70.0	10
	Potassium	0.89	1.5	1.8	2.1	2.1	6
	Sodium-adsorption ratio (unitless)	0.080	0.10	0.16	0.49	1.3	6
	Alkalinity (as $CaCO_3$)	148	174	201	207	233	11
	Chloride	2.0	3.7	8.0	19.8	72.0	11
	Fluoride	0.10	0.11	0.25	0.58	3.8	8
	Silica	9.4	11.0	17.4	20.0	29.7	7
	Sulfate	4.0	12.0	474	542	1,590	11
	Total dissolved solids	194	228	906	959	2,370	11
	Nitrate+nitrite (as N)	--	1.2	2.2	2.2	2.2	3
	Nitrate (as N)	--	0.38	0.82	1.8	28.7	9
	Boron	--	40.0	40.0	180	300	5
	Iron, unfiltered	50.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	230	770	1,230	1,230	3

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer (Casper Formation)	pH (standard units)	6.7	7.4	7.7	7.9	8.8	73
	Specific conductance (µS/cm)	199	358	391	470	1,750	94
	Hardness (as $CaCO_3$)	12.7	170	200	244	1,000	33
	Calcium	13.0	45.0	52.0	62.0	298	95
	Magnesium	5.0	15.0	19.3	23.8	155	94
	Sodium	0.20	2.0	3.6	7.0	160	96
	Potassium	0.32	0.68	0.93	1.3	8.9	82
	Sodium-adsorption ratio (unitless)	0.040	0.12	0.20	0.70	2.1	18
	Alkalinity (as $CaCO_3$)	81.0	185	206	222	451	96
	Chloride	0.010	0.59	2.0	4.9	83.0	95
	Fluoride	0.050	0.18	0.23	0.40	1.7	57
	Silica	2.9	8.7	9.8	12.0	31.0	73
	Sulfate	2.0	7.0	13.2	38.1	929	96
	Total dissolved solids	102	197	214	266	1,520	90
	Ammonia+organic nitrogen, unfiltered (as N)	0.050	--	--	--	--	1
	Nitrate+nitrite (as N)	--	0.46	1.2	2.0	4.7	12
	Nitrate (as N)	--	0.27	0.69	1.7	5.9	26
	Total nitrogen, unfiltered (as N)	0.12	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.010	--	--	--	0.030	2
	Antimony	<1.0	--	--	--	<1.0	2
	Beryllium	<1.0	--	--	--	<1.0	2
	Boron	--	22.5	49.9	140	270	17
	Manganese	<1.0	--	--	--	<1.0	2
	Manganese, unfiltered	<100	--	--	--	--	1
	Nickel	<20.0	--	--	--	<20.0	2
	Zinc	48.0	--	--	--	127	2
	Gross alpha radioactivity (picocuries per liter)	3.1	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	--	8.5	8.7	9.7	9.7	3
	Radium-226 (picocuries per liter)	--	0.20	1.0	1.0	1.0	3
	Radon-222, unfiltered (picocuries per liter)	--	210	390	1,080	1,080	3
	Tritium, unfiltered (picocuries per liter)	16.6	--	--	--	20.5	2
	Uranium	1.8	--	--	--	2.0	2
Casper aquifer (Fountain Formation)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	403	--	--	--	--	1
	Hardness (as $CaCO_3$)	190	--	--	--	--	1
	Calcium	59.5	--	--	--	--	1
	Magnesium	10.2	--	--	--	--	1
	Sodium	7.9	--	--	--	--	1

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer (Fountain Formation)—Continued	Potassium	1.8	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.25	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	191	--	--	--	--	1
	Chloride	4.5	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	10.7	--	--	--	--	1
	Sulfate	14.6	--	--	--	--	1
	Total dissolved solids	224	--	--	--	--	1
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	0.32	--	--	--	--	1
	Nitrate (as N)	<0.32	--	--	--	--	1
	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	<0.010	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	5,720	--	--	--	--	1
Madison aquifer	pH (standard units)	7.7	7.8	7.8	7.8	7.8	4
	Specific conductance (µS/cm)	280	325	394	426	434	4
	Hardness (as $CaCO_3$)	174	--	--	--	--	1
	Calcium	36.9	43.0	49.5	54.5	59.0	4
	Magnesium	9.1	10.6	16.8	23.0	24.5	4
	Sodium	1.0	1.0	3.3	5.8	6.0	4
	Potassium	0.30	0.65	1.4	1.9	2.0	4
	Sodium-adsorption ratio (unitless)	0.20	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	139	162	195	218	229	4
	Chloride	0.60	0.88	1.2	1.4	1.4	4
	Fluoride	0.050	0.11	0.17	0.19	0.20	4
	Silica	6.8	7.9	9.2	18.2	27.0	4
	Sulfate	6.2	10.8	17.5	22.3	25.0	4
	Total dissolved solids	219	--	231	--	257	3
	Nitrate+nitrite (as N)	0.87	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.13	--	--	--	--	1
	Iron, unfiltered	<50.0	--	--	--	<50.0	2
	Tritium, unfiltered (picocuries per liter)	124	--	--	--	--	1
Fremont Canyon aquifer	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	387	--	--	--	--	1
	Calcium	62.0	--	--	--	--	1
	Magnesium	17.0	--	--	--	--	1
	Sodium	0.80	--	--	--	--	1
	Potassium	0.70	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	269	--	--	--	--	1
	Chloride	6.9	--	--	--	--	1

Appendix E5. Summary statistics for environmental water samples, Laramie Mountains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fremont Canyon aquifer—Continued	Fluoride	0.090	--	--	--	--	1
	Sulfate	1.0	--	--	--	--	1
	Iron, unfiltered	<10.0	--	--	--	--	1
Precambrian basal confining unit	pH (standard units)	6.2	6.7	7.0	7.6	7.8	13
	Specific conductance (µS/cm)	53.0	120	228	312	500	12
	Hardness (as $CaCO_3$)	20.0	22.6	105	164	168	7
	Calcium	6.3	14.8	27.0	38.0	89.0	15
	Magnesium	1.1	2.9	5.7	8.3	26.7	15
	Sodium	0.90	2.6	4.3	5.6	7.7	15
	Potassium	0.59	0.75	0.98	1.4	2.8	12
	Sodium-adsorption ratio (unitless)	0.18	0.22	0.27	0.30	0.30	4
	Alkalinity (as $CaCO_3$)	20.0	45.1	121	178	278	15
	Chloride	0.11	0.60	2.9	6.0	15.0	15
	Fluoride	0.10	0.15	0.30	0.45	0.71	8
	Silica	7.6	8.7	11.6	16.8	31.4	12
	Sulfate	1.0	4.0	6.0	11.0	20.0	15
	Total dissolved solids	45.0	63.0	159	179	282	15
	Ammonia (as N)	<0.010	--	--	--	--	1
	Nitrate+nitrite (as N)	1.3	--	--	--	--	1
	Nitrate (as N)	--	0.68	1.3	5.5	9.3	4
	Nitrite (as N)	<0.010	--	--	--	--	1
	Orthophosphate (as P)	0.020	--	--	--	--	1
	Boron	40.0	--	--	--	120	2
	Radon-222, unfiltered (picocuries per liter)	8,190	--	--	--	--	1

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Dissolved oxygen	0.10	0.40	0.60	2.0	5.4	13
	pH (standard units)	6.8	7.3	7.5	7.7	8.5	34
	Specific conductance (µS/cm)	265	871	1,540	2,870	8,280	33
	Hardness (as $CaCO_3$)	130	150	530	840	4,100	17
	Calcium	36.0	41.0	139	228	469	17
	Magnesium	10.0	14.0	52.0	82.0	735	17
	Sodium	6.0	11.0	120	250	1,330	17
	Potassium	1.5	2.4	6.6	12.0	38.7	16
	Sodium-adsorption ratio (unitless)	0.20	0.40	2.4	3.7	13.0	17
	Alkalinity (as $CaCO_3$)	120	150	252	344	490	17
	Bromide	0.19	--	--	--	--	1
	Chloride	3.3	8.5	25.0	39.0	200	17
	Fluoride	0.10	0.30	0.65	1.1	4.3	12
	Silica	13.0	14.7	16.0	26.0	41.0	15
	Sulfate	7.4	31.0	480	950	5,320	17
	Total dissolved solids	165	200	1,110	1,690	8,950	17
	Ammonia (as N)	--	0.001	0.006	0.025	0.45	17
	Nitrate+nitrite (as N)	--	0.55	2.2	5.7	207	28
	Nitrate (as N)	--	0.087	0.47	2.5	9.8	18
	Nitrite (as N)	--	0.002	0.005	0.011	0.084	17
	Orthophosphate (as P)	--	0.008	0.013	0.020	0.11	17
	Phosphorus, unfiltered (as P)	--	0.013	0.020	0.030	0.060	7
	Aluminum	<1.6	--	--	--	--	1
	Antimony	<0.30	--	--	--	--	1
	Arsenic	--	0.65	0.94	2.0	3.0	5
	Barium	<10.0	--	--	--	196	2
	Beryllium	<0.06	--	--	--	--	1
	Boron	--	240	510	820	1,200	11
	Cadmium	--	0.14	0.26	1.0	1.0	5
	Chromium	--	0.80	1.0	2.0	3.0	5
	Cobalt	0.27	--	--	--	--	1
	Copper	--	5.0	18.0	53.0	57.7	5
	Iron	<8.0	--	--	--	--	1
	Iron, unfiltered	70.0	--	--	--	--	1
	Lithium	21.3	--	--	--	--	1
	Manganese	0.50	--	--	--	--	1
	Mercury	--	0.10	0.10	0.30	0.30	3
	Molybdenum	--	2.0	2.0	4.0	27.0	5
	Nickel	3.8	--	--	--	5.0	2
	Selenium	--	4.5	20.5	63.0	120	6
	Strontium	462	--	--	--	--	1
	Vanadium	--	1.2	2.0	3.0	5.0	5

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers—Continued	Zinc	--	10.0	24.0	30.0	150	5
	Gross beta radioactivity (picocuries per liter)	160	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	3,810	--	--	--	--	1
	Uranium	--	38.1	74.5	161	230	4
Quaternary terrace-deposit aquifers	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	3,590	--	--	--	--	1
	Hardness (as $CaCO_3$)	1,400	--	--	--	--	1
	Calcium	223	--	--	--	--	1
	Magnesium	195	--	--	--	--	1
	Sodium	411	--	--	--	--	1
	Potassium	7.1	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	4.9	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	319	--	--	--	--	1
	Chloride	295	--	--	--	--	1
	Fluoride	1.0	--	--	--	--	1
	Silica	15.0	--	--	--	--	1
	Sulfate	1,510	--	--	--	--	1
	Total dissolved solids	2,890	--	--	--	--	1
	Nitrate+nitrite (as N)	8.1	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Barium	<10.0	--	--	--	--	1
	Boron	740	--	--	--	5,700	2
	Cadmium	<1.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	5.0	--	--	--	--	1
	Lead	5.0	--	--	--	--	1
	Mercury	0.40	--	--	--	--	1
	Molybdenum	15.0	--	--	--	--	1
	Nickel	4.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Vanadium	<1.0	--	--	--	--	1
	Zinc	<10.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	1.2	--	--	--	--	1
	Uranium	<0.40	--	--	--	--	1
Aquifers in Quaternary dune sand (eolian) deposits	pH (standard units)	8.0	8.1	8.2	8.4	8.8	9
	Specific conductance (µS/cm)	788	1,530	2,030	2,670	3,930	9
	Hardness (as $CaCO_3$)	51.2	229	264	600	1,350	9
	Calcium	11.5	59.1	64.0	122	284	9

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in Quaternary dune sand (eolian) deposits—Continued	Magnesium	5.4	19.9	26.6	48.7	155	9
	Sodium	158	252	356	382	633	9
	Potassium	3.5	4.5	6.4	8.2	11.6	9
	Alkalinity (as $CaCO_3$)	176	256	285	299	318	9
	Chloride	25.4	63.4	98.9	124	157	9
	Sulfate	158	338	525	907	1,710	9
	Total dissolved solids	466	1,020	1,340	2,000	3,260	9
	Nitrate+nitrite (as N)	--	8.3	13.4	21.1	21.7	9
	Arsenic	<1.0	--	--	--	--	1
	Barium	100	--	--	--	--	1
	Boron	580	--	--	--	--	1
	Cadmium	1.0	--	--	--	--	1
	Chromium	10.0	--	--	--	--	1
	Copper	10.0	--	--	--	--	1
	Iron, unfiltered	--	10.9	30.0	108	1,920	9
	Lead	<5.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Molybdenum	6.0	--	--	--	--	1
	Nickel	2.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Vanadium	<1.0	--	--	--	--	1
	Zinc	40.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	32.0	--	--	--	--	1
	Uranium	30.0	--	--	--	--	1
White River aquifer and confining unit	pH (standard units)	6.0	6.8	7.4	7.5	9.5	17
	Specific conductance (µS/cm)	90.0	205	298	333	529	18
	Hardness (as $CaCO_3$)	40.0	60.0	100	140	190	18
	Calcium	9.6	18.0	31.5	44.0	61.0	18
	Magnesium	2.2	3.9	5.7	7.4	10.0	18
	Sodium	2.3	6.5	12.5	22.0	96.0	18
	Potassium	1.2	2.4	3.2	4.0	6.6	18
	Sodium-adsorption ratio (unitless)	0.10	0.30	0.55	0.90	6.6	18
	Alkalinity (as $CaCO_3$)	45.0	91.0	132	158	200	18
	Chloride	0.20	1.3	2.7	3.6	18.0	18
	Fluoride	0.10	0.10	0.30	0.30	0.60	18
	Silica	10.0	20.0	24.5	43.0	94.0	18
	Sulfate	2.1	6.0	10.5	20.0	92.0	18
	Total dissolved solids	69.0	131	191	228	400	18
	Nitrate+nitrite (as N)	1.3	--	--	--	--	1
	Nitrate (as N)	--	0.16	0.47	0.79	1.6	15

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
White River aquifer and confining unit—Continued	Boron	70.0	--	--	--	--	1
	Iron, unfiltered	--	30.0	60.0	95.0	1,400	16
	Uranium	1.7	--	--	--	--	1
Wagon Bed aquifer and confining unit	pH (standard units)	6.9	--	6.9	--	7.6	3
	Specific conductance (µS/cm)	292	--	469	--	485	3
	Hardness (as $CaCO_3$)	110	--	180	--	200	3
	Calcium	26.0	--	55.0	--	59.0	3
	Magnesium	11.0	--	11.0	--	13.0	3
	Sodium	19.0	--	20.0	--	22.0	3
	Potassium	3.6	--	6.2	--	6.2	3
	Sodium-adsorption ratio (unitless)	0.60	--	0.70	--	0.80	3
	Alkalinity (as $CaCO_3$)	144	--	230	--	236	3
	Chloride	1.3	--	3.5	--	3.9	3
	Fluoride	0.50	--	0.50	--	0.50	3
	Silica	53.0	--	55.0	--	71.0	3
	Sulfate	3.2	--	7.2	--	9.8	3
	Total dissolved solids	213	--	310	--	310	3
Wind River aquifer	pH (standard units)	6.7	7.5	7.7	8.2	8.4	14
	Specific conductance (µS/cm)	134	403	553	939	1,710	14
	Hardness (as $CaCO_3$)	52.0	56.0	110	190	490	14
	Calcium	16.0	17.0	33.5	58.0	120	14
	Magnesium	2.9	3.9	6.2	12.0	46.0	14
	Sodium	1.4	47.0	67.0	120	270	14
	Potassium	1.6	2.8	4.5	6.4	8.4	14
	Sodium-adsorption ratio (unitless)	0.10	1.5	2.4	6.1	7.4	14
	Alkalinity (as $CaCO_3$)	57.0	102	133	172	230	14
	Chloride	2.0	3.1	8.9	19.0	32.0	14
	Fluoride	0.10	0.10	0.30	0.60	0.70	14
	Silica	9.5	12.0	13.5	17.0	23.0	14
	Sulfate	2.8	63.0	93.0	270	790	14
	Total dissolved solids	82.0	241	346	619	1,310	14
	Nitrate (as N)	--	0.020	0.16	0.25	0.56	13
	Orthophosphate (as P)	0.007	--	--	--	0.091	2
	Aluminum	220	--	--	--	--	1
	Boron	--	70.0	125	415	700	4
	Iron, unfiltered	--	55.0	130	270	460	12
	Gross beta radioactivity (picocuries per liter)	9.0	--	--	--	--	1
	Uranium	--	0.30	0.60	8.3	8.3	3
Lance aquifer	pH (standard units)	7.0	7.0	7.8	8.4	8.4	7
	Specific conductance (µS/cm)	544	--	550	--	1,710	3
	Hardness (as $CaCO_3$)	38.0	135	220	270	830	8

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Lance aquifer—Continued	Calcium	10.7	43.5	55.0	75.0	174	8
	Magnesium	2.8	8.5	16.5	24.5	97.0	8
	Sodium	36.0	77.5	87.5	113	345	8
	Potassium	2.8	--	5.0	--	9.2	3
	Sodium-adsorption ratio (unitless)	1.0	1.2	2.7	3.0	9.4	6
	Alkalinity (as $CaCO_3$)	98.0	170	185	240	459	8
	Chloride	8.0	10.5	12.0	18.5	37.0	8
	Fluoride	0.45	--	0.48	--	0.70	3
	Silica	7.7	11.6	15.0	21.0	21.0	7
	Sulfate	69.0	94.0	145	286	712	7
	Total dissolved solids	350	380	557	624	1,270	7
	Nitrate+nitrite (as N)	<0.050	--	--	--	--	1
	Nitrate (as N)	<0.050	--	--	--	0.090	2
	Boron	40.0	--	--	--	--	1
	Iron, unfiltered	535	--	--	--	670	2
	Manganese, unfiltered	57.0	--	--	--	110	2
	Gross beta radioactivity (picocuries per liter)	3.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	2.9	--	--	--	--	1
	Uranium	<1.0	--	--	--	<1.0	2
Fox Hills aquifer	pH (standard units)	7.2	7.2	8.2	8.4	8.5	6
	Specific conductance (µS/cm)	2,190	--	2,200	--	2,550	3
	Hardness (as $CaCO_3$)	49.0	56.0	73.3	240	380	6
	Calcium	9.0	15.0	23.5	53.0	88.0	6
	Magnesium	3.0	3.0	6.0	27.0	40.0	6
	Sodium	168	298	457	580	650	6
	Potassium	2.0	--	2.0	--	2.0	3
	Sodium-adsorption ratio (unitless)	3.7	--	8.3	--	20.1	3
	Alkalinity (as $CaCO^3$)	133	180	245	320	361	6
	Chloride	16.0	18.0	52.5	70.0	100	6
	Sulfate	401	410	672	980	1,200	6
	Total dissolved solids	943	1,040	1,390	1,730	2,050	6
Mesaverde aquifer	pH (standard units)	7.2	--	--	--	8.5	2
	Specific conductance (µS/cm)	2,650	--	--	--	7,110	2
	Hardness (as CaCO3)	10.0	--	--	--	--	1
	Calcium	1.0	--	--	--	--	1
	Magnesium	1.8	--	--	--	--	1
	Sodium	670	--	--	--	--	1
	Potassium	2.2	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	93.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	872	--	--	--	--	1

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mesaverde aquifer—Continued	Chloride	52.0	--	--	--	--	1
	Fluoride	3.1	--	--	--	--	1
	Silica	22.0	--	--	--	--	1
	Sulfate	515	--	--	--	--	1
	Total dissolved solids	1,790	--	--	--	--	1
	Nitrate (as N)	0.023	--	--	--	--	1
	Boron	1,400	--	--	--	--	1
	Iron, unfiltered	80.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	1,140	--	--	--	--	1
Cody confining unit	Dissolved oxygen	0.50	0.50	0.50	0.60	1.8	5
	pH (standard units)	6.8	7.3	7.5	7.7	7.9	34
	Specific conductance (µS/cm)	652	2,350	4,020	6,500	31,400	31
	Hardness (as $CaCO_3$)	51.0	723	1,630	3,150	26,600	32
	Calcium	14.0	165	295	480	1,100	32
	Magnesium	3.8	84.5	165	420	6,200	32
	Sodium	38.0	260	608	1,480	16,000	32
	Potassium	3.2	5.7	9.8	22.0	120	31
	Sodium-adsorption ratio (unitless)	0.98	4.1	7.0	10.8	77.0	32
	Alkalinity (as $CaCO_3$)	17.0	269	377	502	797	32
	Bromide	1.6	--	--	--	--	1
	Chloride	9.5	47.0	89.5	160	950	32
	Fluoride	0.30	0.45	0.65	2.2	23.0	12
	Silica	8.1	13.0	16.5	18.0	24.0	12
	Sulfate	140	1,050	2,120	3,300	68,000	32
	Total dissolved solids	422	1,960	3,630	6,230	98,500	31
	Nitrate+nitrite (as N)	--	3.2	15.0	56.0	1,600	21
	Nitrate (as N)	1,300	--	--	--	--	1
	Orthophosphate (as P)	<1.6	--	--	--	--	1
	Barium	65.0	--	--	--	100	2
	Beryllium	<20.0	--	--	--	--	1
	Boron	--	420	660	1,100	1,900	23
	Chromium	--	1.4	2.2	3.6	27.0	22
	Cobalt	<120	--	--	--	--	1
	Copper	--	5.0	10.2	20.8	180	22
	Iron	<120	--	--	--	--	1
	Iron, unfiltered	430	--	--	--	--	1
	Lithium	4,600	--	--	--	--	1
	Manganese	51.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Molybdenum	--	2.8	6.1	13.3	48.0	22
	Nickel	2.0	--	--	--	<400	2

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cody confining unit—Continued	Selenium	--	18.0	340	1,400	20,000	33
	Strontium	13,000	--	--	--	--	1
	Vanadium	--	1.9	4.6	11.1	41.0	22
	Zinc	--	20.0	40.0	80.0	800	22
	Gross beta radioactivity (picocuries per liter)	1.7	--	--	--	--	1
	Tritium, unfiltered (picocuries per liter)	--	57.0	58.0	162	182	6
	Uranium	<0.40	--	--	--	--	1
Steele confining unit	pH (standard units)	8.4	--	8.4	--	8.5	3
	Specific conductance (µS/cm)	895	--	2,170	--	4,130	3
	Hardness (as $CaCO_3$)	40.0	--	500	--	1,100	3
	Calcium	12.0	--	90.0	--	180	3
	Magnesium	2.4	--	67.0	--	150	3
	Sodium	180	--	320	--	670	3
	Potassium	4.2	--	5.8	--	6.6	3
	Sodium-adsorption ratio (unitless)	6.2	--	8.9	--	12.0	3
	Alkalinity (as $CaCO_3$)	289	--	310	--	664	3
	Chloride	0.10	--	12.0	--	15.0	3
	Fluoride	0.10	--	0.20	--	0.80	3
	Silica	9.6	--	15.0	--	23.0	3
	Sulfate	110	--	840	--	1,700	3
	Total dissolved solids	511	--	1,530	--	3,160	3
	Nitrate (as N)	--	0.41	0.43	1.4	1.4	3
	Boron	--	30.0	200	950	950	3
	Iron, unfiltered	--	400	400	540	540	3
Frontier aquifer	pH (standard units)	7.9	8.0	8.2	8.5	9.6	9
	Specific conductance (µS/cm)	1,000	1,290	2,200	2,830	4,210	9
	Hardness (as $CaCO_3$)	3.0	11.0	271	508	1,800	9
	Calcium	0.40	3.2	69.4	141	275	9
	Magnesium	0.60	1.0	23.8	35.8	271	9
	Sodium	34.5	107	284	580	984	9
	Potassium	1.2	1.7	2.4	2.8	6.0	9
	Sodium-adsorption ratio (unitless)	77.0	--	110	--	180	3
	Alkalinity (as $CaCO_3$)	193	224	309	757	1,450	9
	Chloride	2.4	8.6	21.2	74.4	208	9
	Fluoride	1.9	--	7.3	--	12.0	3
	Silica	6.4	--	8.5	--	9.0	3
	Sulfate	64.0	317	425	646	1,900	9
	Total dissolved solids	708	978	1,470	1,780	3,570	9
	Ammonia+organic nitrogen, unfiltered (as N)	0.72	--	--	--	--	1

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer—Continued	Ammonia, unfiltered (as N)	0.64	--	--	--	--	1
	Nitrate+nitrite (as N)	--	0.019	0.81	10.7	17.1	6
	Nitrate+nitrite, unfiltered (as N)	0.020	--	--	--	--	1
	Nitrate (as N)	0.050	--	--	--	--	1
	Organic nitrogen, unfiltered (as N)	0.080	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.74	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.030	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	2.0	--	--	--	--	1
	Beryllium	<10.0	--	--	--	--	1
	Boron	--	1,400	1,900	3,100	3,100	3
	Copper	<2.0	--	--	--	--	1
	Iron	110	--	--	--	--	1
	Iron, unfiltered	--	62.0	252	461	2,650	8
	Lead	2.0	--	--	--	--	1
	Lithium	40.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Manganese, unfiltered	<10.0	--	--	--	--	1
	Mercury	<0.50	--	--	--	--	1
	Molybdenum	1.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	20.0	2
	Zinc	20.0	--	--	--	--	1
Cloverly Formation	pH (standard units)	8.0	8.2	8.5	8.8	8.9	5
	Specific conductance (µS/cm)	491	538	1,940	2,470	2,540	5
	Hardness (as $CaCO_3$)	2.0	--	--	--	30.0	2
	Calcium	1.0	1.0	1.0	1.0	9.8	5
	Magnesium	1.0	1.0	1.0	1.2	1.3	4
	Sodium	117	149	442	600	600	5
	Potassium	0.30	1.2	1.3	1.6	2.2	5
	Sodium-adsorption ratio (unitless)	41.0	--	--	--	48.0	2
	Alkalinity (as $CaCO_3$)	210	228	288	400	952	5
	Chloride	2.5	6.7	12.2	18.0	64.7	5
	Fluoride	0.70	0.70	2.4	2.8	9.4	5
	Silica	18.1	19.0	19.0	23.6	27.0	5
	Sulfate	34.2	74.0	330	546	958	5
	Total dissolved solids	322	402	1,290	1,570	1,770	5
	Ammonia (as N)	--	0.18	0.45	0.98	0.98	3
	Nitrate (as N)	0.050	--	--	--	--	1
	Nitrite (as N)	<0.10	--	--	--	<0.10	2
	Boron	--	380	1,180	1,300	3,510	5
	Iron, unfiltered	50.0	--	--	--	120	2

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cloverly Formation—Continued	Manganese	--	20.0	20.0	120	120	3
	Vanadium	<100	--	--	--	<100	2
Casper aquifer	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	4,400	--	--	--	--	1
	Hardness (as $CaCO_3$)	1,800	--	--	--	--	1
	Calcium	510	--	--	--	--	1
	Magnesium	120	--	--	--	--	1
	Sodium	160	--	--	--	--	1
	Potassium	23.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	1.7	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	89.0	--	--	--	--	1
	Chloride	56.0	--	--	--	--	1
	Fluoride	3.0	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	2,000	--	--	--	--	1
	Total dissolved solids	2,930	--	--	--	--	1
	Ammonia+organic nitrogen, unfiltered (as N)	0.13	--	--	--	--	1
	Nitrate+nitrite (as N)	0.12	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.25	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.010	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Madison aquifer	pH (standard units)	7.3	7.4	7.4	7.5	7.6	4
	Specific conductance (µS/cm)	3,660	--	4,140	--	4,600	3
	Hardness (as $CaCO_3$)	380	1,100	1,250	1,300	1,400	6
	Calcium	110	335	375	460	500	6
	Magnesium	25.0	36.0	46.0	64.0	82.0	6
	Sodium	77.0	452	513	734	1,310	6
	Potassium	9.8	37.0	51.0	58.0	82.0	5
	Sodium-adsorption ratio (unitless)	1.7	6.0	6.4	8.9	15.2	6
	Alkalinity (as $CaCO_3$)	78.0	92.0	102	130	180	6
	Bromide	0.40	--	--	--	--	1
	Chloride	70.0	322	528	623	1,180	6
	Fluoride	1.4	2.7	4.2	4.7	5.0	4
	Silica	19.0	24.5	33.5	38.5	40.0	4
	Sulfate	340	1,160	1,470	1,560	3,230	6
	Total dissolved solids	732	2,920	3,150	3,730	5,680	6
	Ammonia+organic nitrogen, unfiltered (as N)	<0.10	--	--	--	--	1
	Nitrate+nitrite (as N)	5.0	--	--	--	--	1
	Phosphorus (as P)	<0.010	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1

Appendix E6. Summary statistics for environmental water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer—Continued	Arsenic	25.0	--	--	--	--	1
	Barium	<100	--	--	--	--	1
	Boron	--	455	710	955	1,200	4
	Iron	2,400	--	--	--	--	1
	Lithium	150	--	--	--	--	1
	Manganese	300	--	--	--	--	1
	Mercury	<0.50	--	--	--	--	1
	Molybdenum	27.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	1,600	--	--	--	--	1
	Zinc	30.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	350	--	--	--	--	1

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Dissolved oxygen	0.20	1.3	3.5	4.9	7.5	13
	pH (standard units)	6.6	7.2	7.4	7.6	8.6	127
	Specific conductance (µS/cm)	295	710	935	1,080	4,920	127
	Hardness (as $CaCO_3$)	46.0	185	270	320	480	56
	Calcium	16.0	56.0	77.0	98.0	140	57
	Magnesium	1.5	12.0	17.0	21.0	37.0	57
	Sodium	7.3	45.0	64.0	92.0	350	62
	Potassium	1.9	6.3	8.9	12.0	26.0	55
	Sodium-adsorption ratio (unitless)	0.23	1.2	1.6	2.6	11.0	54
	Alkalinity (as $CaCO_3$)	86.9	197	243	285	460	60
	Chloride	1.7	10.5	15.0	18.0	38.0	56
	Fluoride	0.20	0.40	0.64	0.80	1.6	58
	Silica	7.2	27.5	42.0	50.0	62.0	56
	Sulfate	10.0	63.0	159	210	700	58
	Total dissolved solids	207	442	528	658	1,530	55
	Ammonia (as N)	--	0.004	0.014	0.040	2.4	65
	Nitrate+nitrite (as N)	--	1.6	4.4	9.1	21.0	92
	Nitrate (as N)	--	0.27	0.74	2.0	17.2	96
	Nitrite (as N)	--	0.001	0.003	0.007	0.15	66
	Orthophosphate (as P)	--	0.020	0.030	0.050	0.18	65
	Phosphorus, unfiltered (as P)	--	0.013	0.018	0.025	0.060	9
	Antimony	<1.0	--	--	--	--	1
	Arsenic	5.0	--	--	--	<10.0	2
	Barium	80.0	--	--	--	<100	2
	Beryllium	<0.50	--	--	--	--	1
	Boron	--	90.0	115	220	880	46
	Cadmium	<0.50	--	--	--	<10.0	2
	Chromium	<50.0	--	--	--	<50.0	2
	Copper	<10.0	--	--	--	--	1
	Iron	--	10.0	20.0	30.0	50.0	13
	Iron, unfiltered	--	10.0	20.0	60.0	5,600	33
	Lead	<1.0	--	--	--	<50.0	2
	Mercury	<0.50	--	--	--	<1.0	2
	Nickel	<20.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	495	535	760	980	4
Quaternary terrace-deposit aquifers	Dissolved oxygen	0.20	2.7	5.1	5.9	6.3	8
	pH (standard units)	6.7	7.4	7.5	7.8	8.0	47
	Specific conductance (µS/cm)	335	610	808	1,060	1,970	47
	Hardness (as $CaCO_3$)	120	170	215	320	497	12
	Calcium	42.0	50.0	67.5	101	120	12
	Magnesium	4.4	9.0	12.0	17.0	48.0	12

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers—Continued	Sodium	10.0	10.0	20.0	42.5	57.0	12
	Potassium	0.70	2.8	4.7	11.5	16.0	8
	Sodium-adsorption ratio (unitless)	0.30	0.32	0.95	1.1	1.2	8
	Alkalinity (as $CaCO_3$)	134	147	163	223	280	12
	Chloride	5.0	10.5	12.5	17.0	26.0	12
	Fluoride	0.20	0.35	0.70	1.1	1.3	12
	Silica	21.0	35.5	43.0	49.0	55.0	12
	Sulfate	8.6	24.0	35.5	160	270	12
	Total dissolved solids	234	282	542	592	727	8
	Ammonia (as N)	--	0.003	0.007	0.014	0.050	35
	Ammonia+organic nitrogen, unfiltered (as N)	0.90	--	--	--	--	1
	Ammonia, unfiltered (as N)	0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	--	3.7	6.9	12.5	24.8	38
	Nitrate+nitrite, unfiltered (as N)	11.0	--	--	--	--	1
	Nitrate (as N)	--	0.73	1.5	3.3	20.4	44
	Organic nitrogen, unfiltered (as N)	0.86	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	12.0	--	--	--	--	1
	Orthophosphate (as P)	--	0.020	0.020	0.030	0.088	35
	Phosphorus, unfiltered (as P)	0.010	--	--	--	0.030	2
	Aluminum	30.0	--	--	--	--	1
	Arsenic	2.0	--	--	--	--	1
	Barium	240	--	--	--	--	1
	Boron	--	10.0	50.0	60.0	150	7
	Cadmium	<1.0	--	--	--	--	1
	Chromium	4.0	--	--	--	--	1
	Copper	1.0	--	--	--	--	1
	Iron	15.0	--	--	--	30.0	2
	Iron, unfiltered	--	20.0	20.0	20.0	30.0	5
	Lead	<1.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
	Mercury	0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	<5.0	2
	Zinc	6.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	8.5	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.14	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	--	270	510	570	570	3
	Uranium	5.8	--	--	--	--	1

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in Quaternary dune sand (eolian) deposits	Dissolved oxygen	4.9	--	--	--	--	1
	pH (standard units)	7.5	--	--	--	7.6	2
	Specific conductance (µS/cm)	763	--	--	--	1,060	2
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	9.1	--	--	--	--	1
	Nitrate (as N)	<9.1	--	--	--	--	1
	Nitrite (as N)	<0.006	--	--	--	--	1
	Orthophosphate (as P)	<0.020	--	--	--	--	1
Ogallala aquifer	Dissolved oxygen	0.10	1.1	2.6	6.9	8.6	8
	pH (standard units)	6.4	7.3	7.5	7.8	8.4	104
	Specific conductance (µS/cm)	128	311	452	760	1,940	105
	Hardness (as $CaCO_3$)	47.0	130	150	229	843	73
	Calcium	17.0	43.0	48.0	71.0	270	74
	Magnesium	1.1	5.7	7.8	13.0	41.0	75
	Sodium	3.2	6.3	9.7	17.0	160	73
	Potassium	1.6	2.1	3.2	4.1	7.4	54
	Sodium-adsorption ratio (unitless)	0.19	0.29	0.35	0.70	3.1	46
	Alkalinity (as $CaCO_3$)	48.0	130	141	176	368	74
	Bromide	0.040	0.040	0.13	0.27	0.31	4
	Chloride	1.0	3.1	5.6	25.0	190	74
	Fluoride	0.10	0.40	0.50	0.70	0.90	72
	Silica	2.5	22.5	26.0	35.1	65.0	61
	Sulfate	1.0	8.9	15.5	34.0	390	74
	Total dissolved solids	70.0	181	227	362	1,270	59
	Ammonia (as N)	--	0.006	0.015	0.054	0.33	15
	Ammonia+organic nitrogen, unfiltered (as N)	0.60	--	--	--	--	1
	Ammonia, unfiltered (as N)	0.070	--	--	--	--	1
	Nitrate+nitrite (as N)	--	2.2	3.6	7.4	22.0	45
	Nitrate+nitrite, unfiltered (as N)	2.6	--	--	--	--	1
	Nitrate (as N)	--	0.46	1.1	2.5	9.0	50
	Organic nitrogen, unfiltered (as N)	0.53	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	3.2	--	--	--	--	1
	Nitrite (as N)	--	0.001	0.002	0.004	0.019	22
	Orthophosphate (as P)	--	0.016	0.022	0.040	1.6	15
	Phosphorus (as P)	--	0.022	0.032	0.066	0.066	3
	Phosphorus, unfiltered (as P)	--	0.030	0.050	0.050	0.070	7
	Dissolved organic carbon	--	0.50	1.1	3.4	3.4	3
	Arsenic	--	1.1	1.6	2.1	4.0	32
	Barium	--	74.2	109	160	260	32
	Boron	--	20.6	28.8	40.4	110	25
	Copper	--	0.96	1.7	3.2	15.0	31

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Ogallala aquifer—Continued	Iron	--	1.1	4.9	20.9	970	33
	Iron, unfiltered	--	30.0	60.0	350	5,800	19
	Lead	--	0.11	0.50	2.2	40.0	33
	Lithium	--	6.0	9.1	16.0	16.0	3
	Manganese	--	0.85	2.4	7.0	77.0	31
	Nickel	--	0.83	0.96	1.1	1.2	9
	Selenium	--	1.2	2.2	4.0	15.0	37
	Strontium	--	188	217	570	570	3
	Zinc	--	4.4	11.0	26.0	250	31
	Gross alpha radioactivity (picocuries per liter)	--	1.1	3.0	5.0	11.0	9
	Gross beta radioactivity (picocuries per liter)	--	1.3	5.1	8.4	13.5	6
	Radium-226 (picocuries per liter)	--	0.20	0.28	0.39	0.60	9
	Radium-228 (picocuries per liter)	--	0.41	0.63	0.98	2.8	9
	Radon-222, unfiltered (picocuries per liter)	--	414	532	630	930	20
	Tritium, unfiltered (picocuries per liter)	25.0	--	--	--	81.9	2
	Uranium	--	1.5	2.4	12.0	14.8	11
Arikaree aquifer	Dissolved oxygen	4.7	--	7.1	--	7.3	3
	pH (standard units)	7.0	7.6	7.8	8.2	8.7	35
	Specific conductance (µS/cm)	285	340	450	746	2,110	37
	Hardness (as $CaCO_3$)	69.0	130	171	208	485	31
	Calcium	21.0	40.5	50.5	62.0	140	32
	Magnesium	0.90	7.1	9.4	12.5	40.0	32
	Sodium	4.3	9.8	16.0	34.0	118	32
	Potassium	1.9	3.5	4.4	5.6	16.0	25
	Sodium-adsorption ratio (unitless)	0.20	0.40	0.53	1.2	4.4	23
	Alkalinity (as $CaCO_3$)	107	141	171	201	320	32
	Chloride	2.0	5.1	6.3	12.0	30.0	32
	Fluoride	0.20	0.35	0.60	0.80	1.3	28
	Silica	18.0	40.0	50.0	55.0	67.0	30
	Sulfate	1.0	13.5	17.0	30.0	300	31
	Total dissolved solids	202	242	265	397	868	26
	Nitrate+nitrite (as N)	--	2.1	3.1	4.1	8.1	15
	Nitrate (as N)	--	1.0	2.1	4.4	8.1	23
	Phosphorus, unfiltered (as P)	--	0.040	0.050	0.060	0.080	9
	Antimony	<1.0	--	--	--	<1.0	2
	Barium	--	100	100	250	250	3
	Beryllium	<0.50	--	--	--	<0.50	2
	Boron	--	26.3	47.3	85.0	580	17

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Arikaree aquifer—Continued	Iron	--	28.3	36.7	50.0	90.0	5
	Iron, unfiltered	--	30.0	90.0	165	260	8
	Molybdenum	<100	--	--	--	--	1
	Vanadium	<100	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	6.2	--	--	--	7.1	2
	Gross beta radioactivity (picocuries per liter)	6.9	--	--	--	7.5	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	<1.0	2
	Radon-222, unfiltered (picocuries per liter)	--	260	520	1,620	7,000	7
	Uranium	--	2.8	6.7	7.0	7.0	3
White River aquifer/confining unit	Dissolved oxygen	3.8	--	--	--	--	1
	pH (standard units)	7.1	7.5	7.8	8.1	8.8	53
	Specific conductance (µS/cm)	269	422	529	1,030	5,450	54
	Hardness (as $CaCO_3$)	0.73	93.0	147	210	960	38
	Calcium	0.11	31.4	53.0	75.1	305	51
	Magnesium	0.11	5.0	8.5	13.0	57.0	51
	Sodium	4.1	17.2	32.0	91.6	1,130	50
	Potassium	2.6	4.4	7.1	14.3	46.0	39
	Sodium-adsorption ratio (unitless)	0.15	1.3	4.6	17.5	309	24
	Alkalinity (as $CaCO_3$)	112	160	211	318	581	51
	Chloride	1.4	4.9	8.4	22.5	277	52
	Fluoride	0.10	0.40	0.60	0.80	3.2	48
	Silica	9.3	21.1	35.4	57.0	72.0	46
	Sulfate	6.7	19.7	28.0	90.5	2,750	52
	Total dissolved solids	182	245	337	701	4,540	43
	Ammonia (as N)	<0.020	--	--	--	--	1
	Nitrate+nitrite (as N)	--	0.75	1.2	1.9	3.8	9
	Nitrate (as N)	--	0.18	0.71	2.8	22.0	28
	Orthophosphate (as P)	0.036	--	--	--	--	1
	Phosphorus, unfiltered (as P)	--	0.010	0.030	0.10	0.10	3
	Boron	--	54.4	131	660	11,000	25
	Iron, unfiltered	--	20.0	50.0	240	6,900	18
	Gross alpha radioactivity (picocuries per liter)	--	6.3	8.6	10.7	13.1	6
	Gross beta radioactivity (picocuries per liter)	--	4.3	7.7	12.2	15.7	4
	Radium-226 (picocuries per liter)	--	0.10	0.14	0.21	0.60	10
	Radon-222, unfiltered (picocuries per liter)	--	420	500	1,140	2,880	7
	Uranium	--	10.0	38.0	120	200	9

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Brule aquifer/confining unit	pH (standard units)	7.0	7.6	7.8	8.0	8.5	51
	Specific conductance (µS/cm)	310	360	457	594	1,080	54
	Hardness (as $CaCO_3$)	31.0	120	140	190	312	51
	Calcium	2.7	32.0	39.0	55.0	91.0	53
	Magnesium	1.0	7.5	11.0	14.0	25.0	53
	Sodium	1.1	18.0	32.0	49.0	217	53
	Potassium	2.3	4.5	6.5	7.9	39.0	30
	Sodium-adsorption ratio (unitless)	0.44	0.60	1.5	1.8	11.0	25
	Alkalinity (as $CaCO_3$)	107	144	162	221	412	54
	Chloride	2.0	6.0	9.0	15.0	45.0	53
	Fluoride	0.20	0.60	0.70	0.80	1.5	50
	Silica	10.4	51.0	55.0	61.0	82.0	47
	Sulfate	9.1	19.0	32.0	44.0	88.0	54
	Total dissolved solids	214	267	357	468	676	32
	Nitrate+nitrite (as N)	--	4.6	5.8	19.0	27.0	7
	Nitrate (as N)	--	0.34	0.92	2.5	11.0	49
	Orthophosphate (as P)	--	0.030	0.030	0.18	0.18	3
	Arsenic	--	3.0	4.0	5.0	5.0	3
	Boron	--	40.0	100	210	16,000	34
	Iron	--	9.6	14.7	22.5	50.0	10
	Iron, unfiltered	--	9.0	21.3	50.0	290	20
	Manganese, unfiltered	<10.0	--	--	--	<10.0	2
	Zinc	--	10.0	20.0	30.0	30.0	3
	Gross alpha radioactivity (picocuries per liter)	2.8	--	--	--	10.3	2
	Radium-226 (picocuries per liter)	--	0.18	0.20	0.30	0.50	5
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	662	--	--	--	731	2
	Uranium	--	16.0	17.0	20.0	20.0	5
Chadron aquifer/confining unit	pH (standard units)	6.5	7.8	8.3	8.6	8.9	10
	Specific conductance (µS/cm)	358	755	822	1,160	1,460	10
	Hardness (as $CaCO_3$)	7.0	10.0	39.5	110	210	8
	Calcium	1.8	2.1	4.0	24.0	54.0	11
	Magnesium	0.30	0.90	2.2	4.9	18.0	11
	Sodium	25.9	40.0	198	262	341	11
	Potassium	3.3	3.8	4.0	7.1	11.0	11
	Sodium-adsorption ratio (unitless)	1.2	1.6	25.0	28.0	33.0	7
	Alkalinity (as $CaCO_3$)	112	169	398	422	604	11
	Chloride	4.5	7.4	10.5	68.0	99.0	11
	Fluoride	0.50	0.60	1.4	1.6	1.9	11

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chadron aquifer/ confining unit—continued	Silica	8.5	8.8	11.0	22.0	50.0	11
	Sulfate	7.7	11.2	29.0	102	298	11
	Total dissolved solids	202	350	512	713	996	11
	Nitrate+nitrite (as N)	--	0.20	0.34	1.1	1.1	3
	Nitrate (as N)	--	0.16	0.25	1.0	3.2	5
	Nitrite (as N)	<0.10	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Boron	--	120	365	420	540	10
	Iron, unfiltered	--	12.6	53.3	610	1,920	7
	Zinc	--	18.0	30.0	590	1,150	4
	Gross alpha radioactivity (picocuries per liter)	8.7	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	13.8	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	405	--	--	--	--	1
Wasatch aquifer	pH (standard units)	5.8	7.3	7.7	7.9	8.5	10
	Specific conductance (µS/cm)	550	620	910	1,450	3,670	10
	Hardness (as $CaCO_3$)	44.0	203	430	807	2,330	9
	Calcium	9.2	46.0	120	220	570	9
	Magnesium	5.1	18.0	31.0	62.0	220	9
	Sodium	9.6	20.0	42.0	49.0	130	9
	Potassium	1.1	4.7	7.4	13.0	18.0	9
	Sodium-adsorption ratio (unitless)	0.30	0.38	0.54	0.65	8.5	9
	Alkalinity (as $CaCO_3$)	130	230	270	489	531	9
	Chloride	4.0	5.4	8.9	24.0	31.0	9
	Fluoride	0.10	0.20	0.30	0.40	1.5	9
	Silica	7.6	8.6	11.0	17.0	27.0	9
	Sulfate	3.0	42.0	100	140	2,100	9
	Total dissolved solids	228	376	516	911	3,200	9
	Ammonia (as N)	--	0.83	1.2	1.6	1.6	3
	Nitrate+nitrite (as N)	--	0.002	0.020	0.90	17.0	9
	Boron	--	115	120	660	1,200	4
	Iron	--	100	630	2,000	15,000	6
	Lead	--	10.0	100	100	100	3
	Manganese	--	5.0	270	380	1,000	6
	Strontium	--	1,800	2,600	3,600	3,900	4
	Zinc	--	40.0	60.0	72.0	72.0	3
	Gross alpha radioactivity (picocuries per liter)	27.0	--	--	--	82.0	2
	Gross beta radioactivity (picocuries per liter)	7.7	--	--	--	12.0	2

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wasatch aquifer—Continued	Radium-226 (picocuries per liter)	0.35	--	--	--	0.88	2
	Radon-222, unfiltered (picocuries per liter)	770	--	--	--	--	1
	Uranium	31.3	--	--	--	94.2	2
Fort Union aquifer	Dissolved oxygen	0.10	--	--	--	--	1
	pH (standard units)	7.0	7.7	8.0	8.2	8.7	5
	Specific conductance (µS/cm)	673	685	925	3,390	3,620	5
	Hardness (as $CaCO_3$)	3.0	36.5	250	865	1,300	4
	Calcium	0.70	8.4	79.0	248	353	4
	Magnesium	0.40	3.9	12.2	57.5	98.0	4
	Sodium	28.0	82.5	150	297	432	4
	Potassium	0.40	2.5	6.6	23.3	38.0	4
	Sodium-adsorption ratio (unitless)	0.60	2.9	6.2	22.6	38.0	4
	Alkalinity (as $CaCO_3$)	234	241	273	326	354	4
	Chloride	3.0	8.0	18.5	38.0	52.0	4
	Fluoride	0.30	0.30	0.30	0.70	1.1	4
	Silica	5.4	7.7	11.5	15.5	18.0	4
	Sulfate	43.0	73.5	141	1,000	1,830	4
	Total dissolved solids	417	421	567	1,870	3,030	4
	Ammonia (as N)	<0.040	--	--	--	--	1
	Nitrate+nitrite (as N)	10.0	--	--	--	--	1
	Nitrate (as N)	--	0.090	0.72	7.5	10.0	5
	Nitrite (as N)	0.006	--	--	--	--	1
	Orthophosphate (as P)	<0.020	--	--	--	--	1
	Boron	--	80.0	140	250	300	4
	Iron, unfiltered	--	45.0	55.0	880	1,700	4
Lance aquifer	pH (standard units)	7.0	7.7	8.3	8.6	9.8	19
	Specific conductance (µS/cm)	391	951	1,170	1,320	2,770	19
	Hardness (as $CaCO_3$)	6.0	12.0	20.0	50.0	170	11
	Calcium	1.7	3.5	6.2	14.0	50.0	15
	Magnesium	0.10	1.1	1.7	4.1	16.3	15
	Sodium	60.0	84.0	273	300	616	15
	Potassium	2.4	3.9	5.4	6.3	18.0	13
	Sodium-adsorption ratio (unitless)	2.0	26.0	29.0	38.5	42.0	8
	Alkalinity (as $CaCO_3$)	167	272	468	555	916	15
	Chloride	3.6	7.5	23.0	37.0	130	15
	Fluoride	0.30	0.60	1.0	2.2	3.4	14
	Silica	11.0	11.0	13.0	17.0	53.0	13
	Sulfate	0.90	30.0	41.0	160	405	15
	Total dissolved solids	264	592	699	820	1,950	13
	Ammonia (as N)	<0.010	--	--	--	0.13	2
	Nitrate+nitrite (as N)	--	0.060	0.20	1.6	4.2	5

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Lance aquifer—Continued	Nitrate (as N)	--	0.050	0.40	2.0	8.8	10
	Orthophosphate (as P)	0.020	--	--	--	0.18	2
	Antimony	<1.0	--	--	--	<5.0	2
	Beryllium	<1.0	--	--	--	<5.0	2
	Boron	--	180	210	770	1,230	11
	Iron	--	40.0	50.0	190	1,220	5
	Iron, unfiltered	--	40.4	75.3	410	970	8
	Selenium	--	1.5	3.3	6.0	50.0	5
	Zinc	--	23.7	40.0	595	1,150	4
	Gross alpha radioactivity (picocuries per liter)	8.5	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	9.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	--	0.13	0.20	0.70	0.90	7
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Uranium	--	15.0	62.0	151	270	7
Fox Hills aquifer	Hardness (as $CaCO_3$)	180	--	--	--	--	1
	Calcium	54.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	9.4	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	179	--	--	--	--	1
	Chloride	7.5	--	--	--	--	1
	Silica	33.0	--	--	--	--	1
	Sulfate	12.0	--	--	--	--	1
	Nitrate (as N)	0.45	--	--	--	--	1
Pierre confining unit	pH (standard units)	9.2	--	--	--	--	1
	Specific conductance (µS/cm)	637	--	--	--	--	1
	Hardness (as $CaCO_3$)	17.6	--	--	--	--	1
	Calcium	5.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	140	--	--	--	--	1
	Potassium	3.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	271	--	--	--	--	1
	Chloride	10.0	--	--	--	--	1
	Fluoride	1.0	--	--	--	--	1
	Silica	9.0	--	--	--	--	1
	Sulfate	25.0	--	--	--	--	1
	Total dissolved solids	379	--	--	--	--	1
	Nitrate+nitrite (as N)	<0.10	--	--	--	--	1
	Nitrite (as N)	<0.10	--	--	--	--	1
	Iron, unfiltered	940	--	--	--	--	1
	Manganese, unfiltered	20.0	--	--	--	--	1

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Pierre confining unit—Continued	Gross alpha radioactivity (picocuries per liter)	<3.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	3.5	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Uranium	0.30	--	--	--	--	1
Cloverly aquifer	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	652	--	--	--	--	1
	Calcium	51.6	--	--	--	--	1
	Magnesium	14.4	--	--	--	--	1
	Sodium	63.7	--	--	--	--	1
	Potassium	3.9	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	233	--	--	--	--	1
	Chloride	5.7	--	--	--	--	1
	Fluoride	0.29	--	--	--	--	1
	Silica	3.8	--	--	--	--	1
	Sulfate	129	--	--	--	--	1
	Total dissolved solids	385	--	--	--	--	1
Sundance aquifer	pH (standard units)	8.4	--	--	--	--	1
	Specific conductance (µS/cm)	475	--	--	--	--	1
	Calcium	11.3	--	--	--	--	1
	Magnesium	0.40	--	--	--	--	1
	Sodium	85.2	--	--	--	--	1
	Potassium	7.8	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	223	--	--	--	--	1
	Chloride	4.3	--	--	--	--	1
	Fluoride	0.080	--	--	--	--	1
	Silica	13.2	--	--	--	--	1
	Sulfate	40.0	--	--	--	--	1
	Total dissolved solids	260	--	--	--	--	1
Chugwater confining unit	pH (standard units)	8.0	--	--	--	--	1
	Specific conductance (µS/cm)	865	--	--	--	--	1
	Calcium	5.6	--	--	--	--	1
	Magnesium	0.90	--	--	--	--	1
	Sodium	151	--	--	--	--	1
	Potassium	7.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	283	--	--	--	--	1
	Chloride	24.1	--	--	--	--	1
	Fluoride	1.5	--	--	--	--	1
	Silica	15.4	--	--	--	--	1
	Sulfate	106	--	--	--	--	1
	Total dissolved solids	436	--	--	--	--	1

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer	pH (standard units)	7.0	7.4	7.9	8.0	8.1	10
	Specific conductance (µS/cm)	316	360	449	570	1,160	10
	Hardness (as $CaCO_3$)	110	162	220	244	300	5
	Calcium	37.0	42.9	51.3	63.3	153	10
	Magnesium	4.8	12.0	20.6	23.0	41.8	10
	Sodium	3.7	8.1	9.6	26.0	45.2	10
	Potassium	0.40	2.0	3.7	5.1	9.0	10
	Sodium-adsorption ratio (unitless)	0.34	--	0.75	--	0.80	3
	Alkalinity (as $CaCO_3$)	118	167	190	223	343	10
	Chloride	1.8	2.5	3.5	11.0	43.4	10
	Fluoride	0.20	0.20	0.44	0.54	0.75	8
	Silica	1.2	8.0	14.8	22.0	29.6	8
	Sulfate	10.0	15.8	26.0	83.0	386	10
	Total dissolved solids	172	207	259	322	765	10
	Nitrate+nitrite (as N)	--	0.49	0.66	0.80	0.80	3
	Nitrate (as N)	--	0.32	0.80	0.86	0.86	3
	Nitrite (as N)	0.020	--	--	--	<0.20	2
	Phosphorus, unfiltered (as P)	0.33	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	--	6.0	11.0	17.0	17.0	3
	Beryllium	<1.0	--	--	--	--	1
	Boron	--	100	120	290	290	3
	Iron, unfiltered	340	--	--	--	--	1
	Manganese	<20.0	--	--	--	<20.0	2
	Nickel	<50.0	--	--	--	--	1
	Zinc	150	--	--	--	300	2
	Gross beta radioactivity (picocuries per liter)	3.8	--	--	--	4.0	2
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	<1.0	2
Hartville aquifer	pH (standard units)	7.6	7.9	8.0	8.1	8.1	9
	Specific conductance (µS/cm)	341	406	472	484	780	10
	Hardness (as $CaCO_3$)	162	--	166	--	216	3
	Calcium	23.0	33.0	40.3	45.8	91.0	10
	Magnesium	6.0	8.8	13.5	17.0	25.0	10
	Sodium	17.9	29.5	48.0	54.0	75.7	10
	Potassium	4.6	8.0	12.0	13.0	13.8	10
	Alkalinity (as $CaCO_3$)	174	187	196	213	242	10
	Chloride	1.0	2.0	4.5	6.0	29.0	10
	Fluoride	0.40	0.70	1.3	1.6	1.7	9
	Silica	4.5	5.2	9.2	16.9	57.5	9
	Sulfate	13.0	21.0	50.0	64.0	185	10

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hartville aquifer—Continued	Total dissolved solids	196	240	286	316	472	10
	Nitrate+nitrite (as N)	--	0.30	1.2	1.2	1.4	5
	Aluminum	<100	--	--	--	<100	2
	Boron	<100	--	--	--	100	2
	Iron	--	17.4	80.0	160	3,960	6
	Iron, unfiltered	--	190	240	1,050	1,050	3
	Manganese, unfiltered	<10.0	--	--	--	20.0	2
	Zinc	<10.0	--	--	--	60.0	2
	Gross beta radioactivity (picocuries per liter)	8.5	--	--	--	9.6	2
	Radon-222, unfiltered (picocuries per liter)	201	--	--	--	--	1
	Uranium	--	9.1	11.0	11.0	11.0	3
Madison aquifer	pH (standard units)	7.1	--	--	--	7.2	2
	Specific conductance (µS/cm)	1,610	--	--	--	1,620	2
	Hardness (as $CaCO_3$)	530	--	--	--	640	2
	Calcium	13.0	--	160	--	190	3
	Magnesium	4.0	--	32.0	--	39.0	3
	Sodium	140	--	140	--	260	3
	Potassium	20.0	--	21.0	--	24.0	3
	Sodium-adsorption ratio (unitless)	2.5	--	--	--	2.6	2
	Alkalinity (as $CaCO_3$)	120	--	126	--	195	3
	Chloride	42.0	--	100	--	130	3
	Fluoride	1.6	--	--	--	2.3	2
	Silica	32.0	--	--	--	39.0	2
	Sulfate	390	--	590	--	620	3
	Total dissolved solids	843	--	1,160	--	1,250	3
	Nitrate+nitrite (as N)	0.090	--	--	--	--	1
	Aluminum	10.0	--	--	--	760	2
	Arsenic	5.0	--	--	--	--	1
	Barium	80.0	--	--	--	--	1
	Beryllium	<1.0	--	--	--	<5.0	2
	Boron	230	--	--	--	310	2
	Cadmium	<1.0	--	--	--	<9.0	2
	Chromium	10.0	--	--	--	<20.0	2
	Cobalt	<20.0	--	--	--	--	1
	Copper	10.0	--	--	--	--	1
	Iron	170	--	--	--	2,600	2
	Iron, unfiltered	1,000	--	--	--	--	1
	Lead	1.0	--	--	--	20.0	2
	Lithium	160	--	--	--	210	2
	Manganese	70.0	--	--	--	450	2

Appendix E7. Summary statistics for environmental water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer—Continued	Manganese, unfiltered	70.0	--	--	--	--	1
	Molybdenum	9.0	--	--	--	13.0	2
	Nickel	1.0	--	--	--	20.0	2
	Strontium	2,300	--	--	--	--	1
	Vanadium	<9.0	--	--	--	--	1
	Zinc	10.0	--	--	--	60.0	2
	Gross beta radioactivity (picocuries per liter)	31.0	--	--	--	51.0	2
	Radium-226 (picocuries per liter)	2.9	--	--	--	--	1
	Tritium, unfiltered (picocuries per liter)	10.0	--	--	--	--	1
	Uranium	2.4	--	--	--	--	1

Appendix F

Summary Statistics for Produced Water Samples

Laura L. Hallberg, and Melanie L. Clark

Appendix F1. Summary statistics for produced-water samples, Sweetwater Arch, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Niobrara confining unit	pH (standard units)	8.3	--	--	--	--	1
	Calcium	32.0	--	--	--	--	1
	Magnesium	29.0	--	--	--	--	1
	Sodium	3,170	--	--	--	--	1
	Potassium	20.0	--	--	--	--	1
	Bicarbonate	702	--	--	--	--	1
	Chloride	4,550	--	--	--	--	1
	Sulfate	37.0	--	--	--	--	1
	Total dissolved solids	8,580	--	--	--	--	1
Frontier aquifer	pH (standard units)	7.5	7.9	8.4	8.6	8.6	4
	Calcium	1.0	1.4	10.4	24.0	29.0	4
	Magnesium	10.0	--	--	--	16.0	2
	Sodium	868	1,820	3,110	3,610	3,770	4
	Potassium	11.0	--	28.8	--	339	3
	Bicarbonate	891	1,120	2,290	4,240	5,250	4
	Chloride	150	1,290	3,050	4,180	4,700	4
	Sulfate	9.6	9.8	27.5	181	317	4
	Total dissolved solids	2,150	4,590	8,290	9,830	10,100	4
	Iron	130	--	--	--	6,070	2
Muddy Sandstone aquifer	pH (standard units)	7.3	8.1	8.6	8.9	9.2	6
	Calcium	3.0	12.0	18.0	27.0	50.0	5
	Magnesium	4.0	5.0	7.0	7.0	16.0	5
	Sodium	584	808	1,310	2,550	2,840	6
	Potassium	39.0	--	--	--	--	1
	Bicarbonate	659	1,440	1,650	1,920	2,200	5
	Carbonate	355	--	--	--	--	1
	Chloride	60.0	280	1,010	2,640	4,170	6
	Sulfate	12.0	--	124	--	428	3
	Total dissolved solids	1,520	1,960	3,260	6,700	7,090	6
	Iron	5,350	--	--	--	11,000	2
Cloverly aquifer	pH (standard units)	7.6	--	8.3	--	8.9	3
	Calcium	9.0	--	13.0	--	96.0	3
	Magnesium	2.0	--	3.0	--	6.0	3
	Sodium	534	--	1,370	--	1,860	3
	Potassium	25.0	--	--	--	--	1
	Bicarbonate	366	--	995	--	1,310	3
	Chloride	8.0	--	1,590	--	2,240	3
	Sulfate	19.0	--	28.0	--	712	3
	Total dissolved solids	1,530	--	3,780	--	5,190	3
	Iron	8,200	--	--	--	--	1

Appendix F1. Summary statistics for produced-water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit	pH (standard units)	8.8	--	--	--	--	1
	Calcium	21.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	1,540	--	--	--	--	1
	Potassium	25.0	--	--	--	--	1
	Bicarbonate	646	--	--	--	--	1
	Chloride	1,780	--	--	--	--	1
	Sulfate	55.0	--	--	--	--	1
	Total dissolved solids	4,330	--	--	--	--	1
Nugget aquifer	pH (standard units)	8.5	--	--	--	8.6	2
	Calcium	14.0	--	21.0	--	54.0	3
	Magnesium	1.0	--	5.0	--	29.0	3
	Sodium	327	--	382	--	1,660	3
	Potassium	56.0	--	--	--	--	1
	Bicarbonate	390	--	413	--	738	3
	Chloride	89.0	--	110	--	2,020	3
	Sulfate	70.0	--	390	--	391	3
	Total dissolved solids	1,080	--	1,150	--	4,710	3
Jelm aquifer	pH (standard units)	8.6	--	--	--	--	1
	Calcium	18.0	--	--	--	--	1
	Magnesium	5.0	--	--	--	--	1
	Sodium	674	--	--	--	--	1
	Bicarbonate	815	--	--	--	--	1
	Chloride	50.0	--	--	--	--	1
	Sulfate	568	--	--	--	--	1
	Total dissolved solids	1,840	--	--	--	--	1
Dinwoody confining unit	pH (standard units)	8.0	--	--	--	--	1
	Calcium	410	--	--	--	--	1
	Magnesium	140	--	--	--	--	1
	Sodium	1,460	--	--	--	--	1
	Potassium	42.0	--	--	--	--	1
	Bicarbonate	195	--	--	--	--	1
	Chloride	80.0	--	--	--	--	1
	Sulfate	4,370	--	--	--	--	1
	Total dissolved solids	6,600	--	--	--	--	1

Appendix F1. Summary statistics for produced-water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Phosphoria aquifer and confining unit	pH (standard units)	6.4	7.5	7.8	8.5	8.9	32
	Calcium	4.0	200	363	533	2,840	35
	Magnesium	3.0	28.0	61.0	105	1,670	34
	Sodium	126	751	1,320	2,020	3,850	35
	Potassium	22.0	32.0	43.5	53.5	59.0	16
	Bicarbonate	134	354	645	1,400	2,950	35
	Chloride	44.0	140	220	339	10,900	35
	Sulfate	644	1,830	2,650	4,000	7,420	35
	Total dissolved solids	1,480	3,700	4,880	7,920	21,800	35
Casper aquifer	pH (standard units)	7.6	--	--	--	--	1
	Calcium	523	--	--	--	--	1
	Magnesium	37.0	--	--	--	--	1
	Sodium	155	--	--	--	--	1
	Bicarbonate	175	--	--	--	--	1
	Chloride	185	--	--	--	--	1
	Sulfate	1,340	--	--	--	--	1
	Total dissolved solids	2,320	--	--	--	--	1
Tensleep aquifer	pH (standard units)	6.7	6.9	7.1	7.9	8.1	9
	Calcium	109	152	219	391	505	12
	Magnesium	12.0	24.5	42.0	54.5	168	12
	Sodium	122	223	347	511	1,570	12
	Potassium	27.0	--	37.0	--	38.0	3
	Bicarbonate	120	195	237	281	656	12
	Chloride	10.0	105	175	293	360	12
	Sulfate	537	662	877	1,650	3,680	12
	Total dissolved solids	1,060	1,440	1,780	2,880	6,250	12
Amsden aquifer	pH (standard units)	8.3	--	--	--	--	1
	Calcium	86.0	--	--	--	--	1
	Magnesium	20.0	--	--	--	--	1
	Sodium	333	--	--	--	--	1
	Bicarbonate	220	--	--	--	--	1
	Chloride	89.0	--	--	--	--	1
	Sulfate	627	--	--	--	--	1
	Total dissolved solids	1,300	--	--	--	--	1

Appendix F1. Summary statistics for produced-water samples, Sweetwater Arch, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer	pH (standard units)	7.6	--	--	--	8.0	2
	Calcium	78.0	--	--	--	141	2
	Magnesium	9.0	--	--	--	59.0	2
	Sodium	124	--	--	--	316	2
	Potassium	27.0	--	--	--	--	1
	Bicarbonate	106	--	--	--	161	2
	Chloride	103	--	--	--	224	2
	Sulfate	456	--	--	--	580	2
	Total dissolved solids	1,090	--	--	--	1,290	2

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Browns Park aquifer	pH (standard units)	6.5	--	--	--	--	1
	Calcium	34.0	--	--	--	--	1
	Magnesium	38.0	--	--	--	--	1
	Sodium	329	--	--	--	--	1
	Bicarbonate	227	--	--	--	--	1
	Chloride	174	--	--	--	--	1
	Sulfate	602	--	--	--	--	1
	Total dissolved solids	1,290	--	--	--	--	1
Hanna aquifer	pH (standard units)	8.8	--	--	--	8.9	2
	Calcium	23.3	--	--	--	74.5	2
	Magnesium	11.0	--	--	--	45.7	2
	Sodium	835	--	--	--	1,210	2
	Potassium	458	--	--	--	483	2
	Bicarbonate	851	--	--	--	2,090	2
	Carbonate	31.2	--	--	--	55.6	2
	Chloride	109	--	--	--	248	2
	Sulfate	1,380	--	--	--	1,620	2
	Total dissolved solids	4,690	--	--	--	5,150	2
	Iron	640	--	--	--	1,880	2
Fort Union aquifer	pH (standard units)	7.4	--	--	--	--	1
	Calcium	1,780	--	--	--	--	1
	Magnesium	81.0	--	--	--	--	1
	Sodium	2,740	--	--	--	--	1
	Potassium	59.0	--	--	--	--	1
	Bicarbonate	207	--	--	--	--	1
	Chloride	7,400	--	--	--	--	1
	Sulfate	207	--	--	--	--	1
	Total dissolved solids	12,400	--	--	--	--	1
Lewis confining unit	pH (standard units)	8.3	--	8.5	--	8.6	3
	Calcium	3.0	--	11.0	--	16.0	3
	Magnesium	1.0	--	3.0	--	6.0	3
	Sodium	450	--	556	--	841	3
	Potassium	8.0	--	--	--	22.0	2
	Bicarbonate	427	--	564	--	1,320	3
	Chloride	150	--	350	--	420	3
	Sulfate	104	--	119	--	530	3
	Total dissolved solids	1,210	--	1,580	--	2,060	3

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mesaverde aquifer	pH (standard units)	7.4	7.7	8.2	8.4	8.8	9
	Calcium	4.9	11.0	11.0	12.0	67.0	9
	Magnesium	2.0	2.2	3.9	11.0	55.0	8
	Sodium	327	503	685	860	3,400	9
	Potassium	7.0	8.3	11.2	21.4	30.0	4
	Bicarbonate	610	1,130	1,600	1,950	3,180	8
	Carbonate	24.0	--	--	--	--	1
	Chloride	36.0	42.0	60.0	252	5,030	9
	Sulfate	3.0	15.0	83.5	292	820	8
	Total dissolved solids	1,090	1,360	1,710	2,130	11,200	9
	Iron	110	--	1,210	--	17,000	3
Cody confining unit	pH (standard units)	8.5	--	--	--	--	1
	Calcium	8.0	--	--	--	--	1
	Magnesium	3.0	--	--	--	--	1
	Sodium	640	--	--	--	--	1
	Potassium	13.0	--	--	--	--	1
	Bicarbonate	1,440	--	--	--	--	1
	Chloride	128	--	--	--	--	1
	Total dissolved solids	1,550	--	--	--	--	1
Shannon Sandstone Member of the Cody Shale	pH (standard units)	8.2	--	--	--	8.3	2
	Calcium	18.0	--	--	--	50.0	2
	Magnesium	8.0	--	--	--	18.0	2
	Sodium	2,990	--	--	--	6,870	2
	Bicarbonate	1,290	--	--	--	1,520	2
	Chloride	3,900	--	--	--	9,700	2
	Sulfate	16.0	--	--	--	21.0	2
	Total dissolved solids	7,570	--	--	--	17,500	2
Steele confining unit	pH (standard units)	7.8	--	--	--	8.3	2
	Calcium	4.0	--	--	--	43.0	2
	Magnesium	7.0	--	--	--	16.0	2
	Sodium	775	--	--	--	4,360	2
	Potassium	25.0	--	--	--	--	1
	Bicarbonate	988	--	--	--	1,860	2
	Chloride	43.0	--	--	--	6,030	2
	Sulfate	121	--	--	--	340	2
	Total dissolved solids	1,910	--	--	--	11,800	2

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Niobrara confining unit	pH (standard units)	7.2	7.4	7.8	8.4	9.7	9
	Calcium	18.0	50.0	326	414	670	9
	Magnesium	6.0	32.0	86.9	171	261	8
	Sodium	475	2,620	11,200	12,300	22,300	9
	Potassium	15.0	57.7	59.0	104	120	6
	Bicarbonate	313	537	699	1,240	1,320	8
	Carbonate	480	--	--	--	--	1
	Chloride	550	3,300	17,300	20,800	32,300	9
	Sulfate	15.0	22.0	213	1,120	2,380	7
	Total dissolved solids	4,360	6,950	29,000	31,100	57,500	9
	Iron	50.0	--	--	--	132,000	2
Frontier aquifer	pH (standard units)	6.2	7.7	8.0	8.6	9.0	24
	Calcium	9.0	17.0	37.0	154	986	26
	Magnesium	0.50	9.0	10.0	48.0	390	25
	Sodium	1,260	3,620	4,540	5,300	17,200	26
	Potassium	17.0	20.0	41.4	78.0	134	16
	Bicarbonate	130	549	805	1,820	4,640	26
	Carbonate	60.0	--	--	--	144	2
	Chloride	1,340	4,150	5,680	10,400	29,000	26
	Sulfate	1.0	6.2	61.0	133	931	23
	Total dissolved solids	3,210	9,270	12,200	17,300	47,600	26
	Iron	40.0	--	--	--	1,000	2
Muddy Sandstone aquifer	pH (standard units)	5.9	7.8	8.1	8.5	8.9	36
	Calcium	2.0	13.0	19.5	39.0	203	38
	Magnesium	1.0	4.0	6.0	15.0	77.0	37
	Sodium	531	1,330	2,440	3,040	6,900	40
	Potassium	4.0	5.0	10.0	20.0	38.0	23
	Bicarbonate	232	1,060	1,200	1,710	3,250	40
	Carbonate	192	--	--	--	--	1
	Chloride	70.0	455	2,340	3,950	9,310	40
	Sulfate	4.0	16.5	113	401	5,740	36
	Total dissolved solids	1,380	3,480	6,250	8,280	18,300	40
Cloverly aquifer	pH (standard units)	6.3	7.9	8.3	8.5	8.9	64
	Calcium	2.0	10.0	20.0	42.4	536	69
	Magnesium	1.0	4.0	8.0	16.0	95.0	62
	Sodium	371	849	1,770	3,050	9,000	72
	Potassium	3.0	6.0	14.0	25.0	58.0	26
	Bicarbonate	49.0	903	1,160	1,350	3,730	72
	Carbonate	60.0	--	--	--	336	2
	Chloride	18.0	317	1,910	3,700	14,300	72
	Sulfate	1.0	28.0	139	505	5,410	66
	Total dissolved solids	1,020	2,220	4,730	7,970	24,100	72
	Iron	12,700	--	--	--	35,400	2

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit	pH (standard units)	7.9	8.2	8.2	8.3	8.9	5
	Calcium	16.0	22.0	24.0	31.0	169	5
	Magnesium	2.0	3.0	5.0	6.0	7.0	5
	Sodium	1,160	1,290	1,820	1,830	4,330	5
	Potassium	16.0	--	--	--	--	1
	Bicarbonate	939	1,090	1,160	1,710	2,240	5
	Chloride	200	200	1,560	2,260	5,400	5
	Sulfate	30.0	34.0	714	1,220	1,530	5
	Total dissolved solids	3,010	3,680	5,170	5,350	10,900	5
Sundance aquifer	pH (standard units)	8.0	8.2	8.3	8.7	8.8	17
	Calcium	2.0	5.0	17.0	39.0	1,290	18
	Magnesium	1.0	2.0	3.0	10.0	123	17
	Sodium	429	575	881	1,190	45,600	18
	Potassium	6.0	10.0	16.0	44.0	80.0	5
	Bicarbonate	500	920	1,090	1,250	1,950	17
	Chloride	28.0	130	178	408	64,000	18
	Sulfate	10.0	86.0	430	1,230	12,100	18
	Total dissolved solids	1,040	1,440	2,240	3,480	123,000	18
Nugget aquifer	pH (standard units)	6.7	7.5	8.1	8.3	9.1	14
	Calcium	4.0	14.5	19.0	33.0	731	16
	Magnesium	1.0	5.0	7.9	23.0	141	14
	Sodium	732	1,560	1,850	3,340	5,200	16
	Potassium	16.0	19.5	26.0	37.5	46.0	4
	Bicarbonate	98.0	908	1,090	2,220	5,270	16
	Carbonate	528	--	--	--	--	1
	Chloride	150	620	2,140	4,190	8,910	16
	Sulfate	6.0	91.0	105	410	950	14
	Total dissolved solids	1,900	3,890	4,900	8,550	16,000	16
	Iron	80.0	--	--	--	7,400	2
Phosphoria aquifer and confining unit	pH (standard units)	6.8	7.3	8.0	8.1	9.1	9
	Calcium	65.0	133	330	866	1,760	11
	Magnesium	9.0	24.0	42.0	125	762	11
	Sodium	170	541	1,600	2,600	4,800	11
	Potassium	10.0	--	--	--	28.0	2
	Bicarbonate	65.0	340	590	769	1,140	11
	Carbonate	96.0	--	--	--	--	1
	Chloride	24.0	377	844	3,240	7,130	11
	Sulfate	30.0	638	2,800	4,210	5,240	11
	Total dissolved solids	1,610	3,240	8,080	10,500	16,400	11

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Forelle aquifer	pH (standard units)	8.2	--	--	--	8.5	2
	Calcium	813	--	--	--	813	2
	Magnesium	189	--	--	--	205	2
	Sodium	26,200	--	--	--	27,600	2
	Bicarbonate	60.0	--	--	--	170	2
	Chloride	32,000	--	--	--	34,000	2
	Sulfate	14,100	--	--	--	14,200	2
	Total dissolved solids	73,400	--	--	--	76,900	2
Casper aquifer	pH (standard units)	5.2	7.5	7.8	8.2	8.9	52
	Calcium	15.0	291	425	630	1,970	55
	Magnesium	10.0	33.0	66.0	104	454	53
	Sodium	424	807	1,810	4,640	27,800	55
	Potassium	13.0	44.0	86.0	220	332	11
	Bicarbonate	60.0	171	270	510	2,200	55
	Chloride	58.0	410	980	4,450	42,900	55
	Sulfate	195	1,970	2,840	3,920	10,200	55
	Total dissolved solids	2,320	3,930	7,630	13,600	75,900	55
Tensleep aquifer	pH (standard units)	6.4	7.2	7.6	8.0	8.4	16
	Calcium	78.0	220	349	580	1,620	20
	Magnesium	10.0	24.0	55.0	86.0	836	19
	Sodium	365	1,130	1,900	2,740	7,990	20
	Potassium	17.0	38.5	62.1	161	258	4
	Bicarbonate	180	329	842	1,760	3,120	19
	Chloride	45.0	464	980	3,450	13,400	20
	Sulfate	18.5	1,700	2,190	3,460	5,510	20
	Total dissolved solids	1,300	5,060	7,480	10,500	23,300	20
	Iron	50.0	--	--	--	--	1
Amsden aquifer	pH (standard units)	6.9	--	7.2	--	8.2	3
	Calcium	299	--	381	--	403	3
	Magnesium	29.0	--	55.0	--	61.0	3
	Sodium	1,810	--	2,540	--	5,420	3
	Potassium	223	--	--	--	--	1
	Bicarbonate	886	--	1,190	--	2,190	3
	Chloride	1,630	--	2,150	--	4,120	3
	Sulfate	2,140	--	2,910	--	4,680	3
	Total dissolved solids	6,480	--	9,450	--	15,700	3

Appendix F2. Summary statistics for produced-water samples, central Wyoming basins (south), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer	pH (standard units)	7.2	--	7.5	--	9.0	3
	Calcium	213	--	257	--	289	3
	Magnesium	34.0	--	56.0	--	111	3
	Sodium	411	--	652	--	2,170	3
	Potassium	20.0	--	--	--	--	1
	Bicarbonate	244	--	282	--	1,250	3
	Chloride	412	--	495	--	2,000	3
	Sulfate	32.0	--	1,300	--	2,450	3
	Total dissolved solids	2,140	--	2,880	--	7,070	3
Aquifers in undifferentiated Cambrian rocks	pH (standard units)	7.6	--	--	--	--	1
	Calcium	459	--	--	--	--	1
	Magnesium	74.0	--	--	--	--	1
	Sodium	1,540	--	--	--	--	1
	Potassium	181	--	--	--	--	1
	Bicarbonate	707	--	--	--	--	1
	Chloride	1,620	--	--	--	--	1
	Sulfate	2,140	--	--	--	--	1
	Total dissolved solids	6,680	--	--	--	--	1
Flathead aquifer	pH (standard units)	7.2	--	--	--	--	1
	Calcium	247	--	--	--	--	1
	Magnesium	6.0	--	--	--	--	1
	Sodium	1,060	--	--	--	--	1
	Potassium	34.0	--	--	--	--	1
	Bicarbonate	110	--	--	--	--	1
	Chloride	730	--	--	--	--	1
	Sulfate	1,800	--	--	--	--	1
	Total dissolved solids	3,930	--	--	--	--	1

Appendix F3. Summary statistics for produced-water samples, Medicine Bow Mountains, Wyoming.

[--, not applicable]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer	pH (standard units)	7.8	--	--	--	--	1
	Calcium	559	--	--	--	--	1
	Magnesium	140	--	--	--	--	1
	Sodium	537	--	--	--	--	1
	Potassium	10.0	--	--	--	--	1
	Bicarbonate	171	--	--	--	--	1
	Chloride	160	--	--	--	--	1
	Sulfate	2,680	--	--	--	--	1
	Total dissolved solids	4,170	--	--	--	--	1

Appendix F4. Summary statistics for produced-water samples, Laramie Mountains, Wyoming.

[--, not applicable]

Hydrogeologic unit	Character or consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Muddy Sandstone aquifer	pH (standard units)	8.7	--	--	--	--	1
	Calcium	6.0	--	--	--	--	1
	Magnesium	2.0	--	--	--	--	1
	Sodium	995	--	--	--	--	1
	Potassium	8.0	--	--	--	--	1
	Bicarbonate	1,260	--	--	--	--	1
	Chloride	50.0	--	--	--	--	1
	Sulfate	900	--	--	--	--	1
	Total dissolved solids	2,680	--	--	--	--	1
Cloverly aquifer	pH (standard units)	8.6	--	--	--	--	1
	Calcium	5.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	509	--	--	--	--	1
	Potassium	6.0	--	--	--	--	1
	Bicarbonate	1,230	--	--	--	--	1
	Chloride	16.0	--	--	--	--	1
	Total dissolved solids	1,200	--	--	--	--	1

Appendix F5. Summary statistics for produced-water samples, central Wyoming basins (north), Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Lance aquifer	pH (standard units)	7.6	8.2	8.4	8.5	8.6	5
	Calcium	7.0	7.0	19.5	33.0	57.0	6
	Magnesium	1.0	2.0	8.0	20.5	28.0	4
	Sodium	345	459	605	1,100	1,300	6
	Potassium	5.0	9.0	11.0	13.0	28.0	5
	Bicarbonate	403	451	628	805	1,810	6
	Chloride	25.0	72.0	155	370	1,150	6
	Sulfate	489	493	528	570	769	6
	Total dissolved solids	1,220	1,300	1,710	3,020	3,410	6
Fox Hills aquifer	pH (standard units)	8.3	--	--	--	--	1
	Calcium	5.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	356	--	--	--	--	1
	Potassium	10.0	--	--	--	--	1
	Bicarbonate	458	--	--	--	--	1
	Carbonate	30.0	--	--	--	--	1
	Sulfate	270	--	--	--	--	1
	Total dissolved solids	1,180	--	--	--	--	1
Mesaverde aquifer	pH (standard units)	7.9	--	8.3	--	8.9	3
	Calcium	10.0	--	16.0	--	35.0	3
	Magnesium	1.0	--	3.0	--	3.0	3
	Sodium	1,160	--	1,220	--	1,600	3
	Potassium	12.0	--	33.0	--	35.0	3
	Bicarbonate	1,180	--	1,680	--	2,150	3
	Chloride	230	--	1,000	--	1,030	3
	Sulfate	318	--	329	--	539	3
	Total dissolved solids	2,880	--	3,210	--	4,190	3
Teapot Sandstone Member of the Mesaverde Formation	pH (standard units)	7.0	--	8.0	--	8.5	3
	Calcium	4.0	--	8.0	--	12.0	3
	Magnesium	1.0	--	1.0	--	5.0	3
	Sodium	483	--	560	--	634	3
	Potassium	5.0	--	6.0	--	7.0	3
	Bicarbonate	915	--	927	--	976	3
	Chloride	42.0	--	64.0	--	176	3
	Sulfate	183	--	244	--	525	3
	Total dissolved solids	1,240	--	1,420	--	1,730	3

Appendix F5. Summary statistics for produced-water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Parkman Sandstone Member of the Mesaverde Formation	pH (standard units)	8.2	--	8.3	--	8.8	3
	Calcium	2.0	--	3.0	--	12.0	3
	Magnesium	1.0	--	--	--	5.0	2
	Sodium	587	591	636	1,320	1,960	4
	Potassium	3.0	--	16.0	--	50.0	3
	Bicarbonate	583	1,030	1,550	2,200	2,780	4
	Carbonate	403	--	--	--	--	1
	Chloride	32.0	36.5	52.5	520	975	4
	Sulfate	16.0	20.0	42.0	397	733	4
	Total dissolved solids	1,370	1,520	1,660	3,220	4,780	4
Shannon Sandstone Member of the Cody Shale	pH (standard units)	5.8	7.2	8.0	8.4	8.8	14
	Calcium	6.0	30.0	47.0	78.0	5,850	25
	Magnesium	2.0	14.5	20.5	48.5	2,900	24
	Sodium	478	3,660	6,110	6,930	9,840	25
	Potassium	15.0	27.0	35.0	48.0	240	9
	Bicarbonate	146	533	800	1,390	2,730	25
	Carbonate	241	--	--	--	--	1
	Chloride	280	5,420	9,200	9,900	31,000	25
	Sulfate	15.0	70.0	108	306	2,780	12
	Total dissolved solids	1,280	9,820	15,700	18,000	48,000	25
Niobrara confining unit	pH (standard units)	8.0	--	--	--	8.2	2
	Calcium	20.0	--	--	--	28.0	2
	Magnesium	10.0	--	--	--	12.0	2
	Sodium	2,350	--	--	--	4,150	2
	Potassium	24.0	--	--	--	--	1
	Bicarbonate	1,150	--	--	--	4,560	2
	Chloride	2,700	--	--	--	3,840	2
	Sulfate	457	--	--	--	--	1
	Total dissolved solids	6,120	--	--	--	10,300	2
Frontier aquifer	pH (standard units)	6.0	7.8	8.2	8.4	9.2	22
	Calcium	8.0	11.0	15.0	97.4	2,160	21
	Magnesium	2.0	3.0	8.5	18.0	148	22
	Sodium	830	1,540	2,800	5,860	10,200	22
	Potassium	3.0	15.5	22.5	67.5	840	16
	Bicarbonate	510	1,230	1,480	2,000	6,830	22
	Carbonate	360	--	--	--	--	1
	Chloride	64.0	650	3,020	6,350	19,800	22
	Sulfate	3.0	76.5	241	824	3,480	20
	Total dissolved solids	2,260	4,630	6,850	15,400	34,100	22
	Iron	40.0	--	--	--	--	1

Appendix F5. Summary statistics for produced-water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wall Creek Sandstone Member of the Frontier Formation	pH (standard units)	6.5	8.3	8.4	8.5	8.7	36
	Calcium	3.0	3.0	6.0	17.5	653	40
	Magnesium	1.0	1.0	2.0	4.5	92.0	40
	Sodium	601	1,060	1,210	1,500	7,210	40
	Potassium	3.0	5.0	5.0	8.0	37.0	28
	Bicarbonate	310	1,460	1,840	2,150	3,680	40
	Carbonate	182	--	--	--	--	1
	Chloride	63.0	440	575	878	9,300	40
	Sulfate	7.0	22.0	148	646	1,450	26
	Total dissolved solids	2,300	2,750	3,010	3,870	18,300	40
Muddy Sandstone aquifer	pH (standard units)	6.8	7.7	8.0	8.3	8.7	51
	Calcium	3.0	16.0	32.0	50.0	130	51
	Magnesium	1.0	7.0	9.0	17.0	62.0	49
	Sodium	521	1,460	3,420	4,570	6,440	51
	Potassium	3.0	5.0	12.0	19.0	40.0	13
	Bicarbonate	659	1,580	2,330	2,900	5,960	51
	Carbonate	108	--	--	--	--	1
	Chloride	40.0	620	2,780	5,720	8,600	51
	Sulfate	2.0	23.0	62.0	206	1,330	46
	Total dissolved solids	1,360	3,700	8,490	11,900	16,700	51
	Iron	54,000	--	--	--	--	1
Cloverly aquifer	pH (standard units)	5.8	7.6	8.1	8.3	8.8	100
	Calcium	2.0	8.7	17.5	56.0	1,220	102
	Magnesium	1.0	2.0	8.5	19.0	270	90
	Sodium	119	805	1,440	3,820	7,170	104
	Potassium	2.0	6.0	10.0	18.5	640	44
	Bicarbonate	73.0	990	1,490	1,890	3,070	103
	Carbonate	38.0	--	--	--	--	1
	Chloride	12.0	295	1,050	3,550	11,200	104
	Sulfate	3.0	76.0	241	633	11,000	100
	Total dissolved solids	1,040	2,050	3,730	10,200	19,600	104
	Iron	50.0	--	170	--	500	3
Morrison confining unit	pH (standard units)	7.0	--	--	--	--	1
	Calcium	489	--	--	--	--	1
	Magnesium	5.0	--	--	--	--	1
	Sodium	6,590	--	--	--	--	1
	Bicarbonate	620	--	--	--	--	1
	Chloride	9,400	--	--	--	--	1
	Sulfate	1,760	--	--	--	--	1
	Total dissolved solids	18,600	--	--	--	--	1

Appendix F5. Summary statistics for produced-water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Sundance aquifer	pH (standard units)	6.3	7.8	8.3	8.7	8.9	15
	Calcium	4.0	7.0	11.0	154	507	17
	Magnesium	2.0	3.0	6.0	31.0	143	15
	Sodium	448	724	864	1,010	5,210	17
	Potassium	5.0	7.0	10.0	10.0	20.0	10
	Bicarbonate	122	610	939	1,160	1,680	17
	Chloride	30.0	148	200	510	2,120	17
	Sulfate	109	325	680	1,270	7,900	17
	Total dissolved solids	1,170	2,100	2,460	3,960	16,600	17
Nugget aquifer	pH (standard units)	8.2	--	--	--	--	1
	Calcium	3.0	--	--	--	--	1
	Sodium	677	--	--	--	--	1
	Bicarbonate	940	--	--	--	--	1
	Chloride	98.0	--	--	--	--	1
	Sulfate	492	--	--	--	--	1
	Total dissolved solids	1,770	--	--	--	--	1
Chugwater aquifer and confining unit	pH (standard units)	8.2	--	--	--	8.3	2
	Calcium	18.0	--	--	--	18.0	2
	Magnesium	5.0	--	--	--	13.0	2
	Sodium	980	--	--	--	1,260	2
	Bicarbonate	440	--	--	--	540	2
	Chloride	240	--	--	--	298	2
	Sulfate	1,240	--	--	--	1,920	2
	Total dissolved solids	2,830	--	--	--	3,760	2
Phosphoria aquifer and confining unit	pH (standard units)	7.9	--	--	--	--	1
	Calcium	541	--	--	--	--	1
	Magnesium	162	--	--	--	--	1
	Sodium	6,990	--	--	--	--	1
	Potassium	100	--	--	--	--	1
	Bicarbonate	549	--	--	--	--	1
	Chloride	5,100	--	--	--	--	1
	Sulfate	9,350	--	--	--	--	1
	Total dissolved solids	22,500	--	--	--	--	1

Appendix F5. Summary statistics for produced-water samples, central Wyoming basins (north), Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Casper aquifer	pH (standard units)	7.0	7.5	7.6	8.0	8.1	5
	Calcium	239	280	408	579	584	7
	Magnesium	3.0	25.0	64.0	105	132	7
	Sodium	427	442	544	930	3,070	7
	Potassium	104	--	--	--	--	1
	Bicarbonate	110	110	170	281	537	7
	Chloride	27.0	50.0	361	512	640	7
	Sulfate	1,370	1,380	2,020	3,440	7,110	7
	Total dissolved solids	2,660	2,940	3,310	5,220	11,200	7
Tensleep aquifer	pH (standard units)	6.5	7.3	7.7	8.0	8.7	45
	Calcium	19.0	211	288	392	618	54
	Magnesium	11.0	50.0	71.0	87.0	223	54
	Sodium	26.0	356	438	607	5,410	54
	Potassium	10.0	20.0	23.0	32.0	37.0	13
	Bicarbonate	20.0	163	243	464	1,350	54
	Chloride	12.0	304	360	411	1,700	54
	Sulfate	79.0	782	1,210	1,720	10,300	54
	Total dissolved solids	1,030	2,080	2,490	3,190	18,400	54
Amsden aquifer	pH (standard units)	7.5	--	--	--	--	1
	Calcium	527	--	--	--	--	1
	Magnesium	131	--	--	--	--	1
	Sodium	409	--	--	--	--	1
	Bicarbonate	127	--	--	--	--	1
	Chloride	364	--	--	--	--	1
	Sulfate	2,040	--	--	--	--	1
	Total dissolved solids	3,540	--	--	--	--	1
Madison aquifer	pH (standard units)	6.2	6.4	6.8	7.2	7.8	8
	Calcium	20.0	174	256	374	500	10
	Magnesium	20.0	37.0	55.0	59.0	66.0	9
	Sodium	171	521	572	921	2,410	10
	Potassium	16.0	40.0	47.0	64.0	99.0	6
	Bicarbonate	146	193	195	268	1,030	10
	Chloride	126	250	430	600	1,180	10
	Sulfate	106	875	1,290	1,570	3,910	10
	Total dissolved solids	1,220	1,940	3,160	3,770	7,770	10

Appendix F6. Summary statistics for produced-water samples, Great Plains, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fort Union aquifer	pH (standard units)	7.3	--	--	--	--	1
	Calcium	71.0	--	--	--	--	1
	Magnesium	34.0	--	--	--	--	1
	Sodium	61.0	--	--	--	--	1
	Potassium	10.0	--	--	--	--	1
	Bicarbonate	342	--	--	--	--	1
	Chloride	8.0	--	--	--	--	1
	Sulfate	181	--	--	--	--	1
	Total dissolved solids	533	--	--	--	--	1
Lance aquifer	pH (standard units)	6.4	8.1	8.3	8.5	8.8	20
	Calcium	2.0	7.5	14.0	19.5	1,310	20
	Magnesium	1.0	3.0	4.0	8.0	446	17
	Sodium	387	513	629	814	1,670	20
	Potassium	8.0	--	10.0	--	20.0	3
	Bicarbonate	171	769	1,010	1,230	1,960	20
	Chloride	60.0	145	210	316	6,000	20
	Sulfate	4.0	50.0	62.0	176	360	20
	Total dissolved solids	1,010	1,300	1,540	2,050	9,620	20
Lewis confining unit	pH (standard units)	7.2	--	--	--	--	1
	Calcium	26.0	--	--	--	--	1
	Magnesium	9.0	--	--	--	--	1
	Sodium	3,260	--	--	--	--	1
	Potassium	59.0	--	--	--	--	1
	Bicarbonate	659	--	--	--	--	1
	Chloride	4,750	--	--	--	--	1
	Sulfate	25.0	--	--	--	--	1
	Total dissolved solids	8,450	--	--	--	--	1
Mesaverde aquifer	pH (standard units)	7.0	--	--	--	8.2	2
	Calcium	26.0	--	--	--	74.0	2
	Magnesium	13.0	--	--	--	14.0	2
	Sodium	1,920	--	--	--	5,980	2
	Bicarbonate	1,410	--	--	--	1,930	2
	Chloride	1,350	--	--	--	8,490	2
	Sulfate	116	--	--	--	704	2
	Total dissolved solids	5,010	--	--	--	15,400	2

Appendix F6. Summary statistics for produced-water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Teapot Sandstone Member of the Mesaverde Formation	pH (standard units)	7.0	7.5	7.7	8.2	8.4	16
	Calcium	10.0	85.0	123	228	1,250	17
	Magnesium	1.0	15.0	22.0	43.0	271	17
	Sodium	1,160	4,560	5,240	5,900	6,490	17
	Potassium	10.0	29.0	46.5	96.5	460	12
	Bicarbonate	451	1,030	1,150	1,390	1,620	17
	Carbonate	48.0	--	--	--	--	1
	Chloride	840	6,300	8,000	9,100	9,900	17
	Sulfate	10.0	32.0	58.0	122	358	13
	Total dissolved solids	2,880	12,000	14,400	16,000	17,200	17
	Iron	1,000	--	--	--	--	1
Parkman Sandstone Member of the Mesaverde Formation	pH (standard units)	7.0	7.5	8.4	8.9	8.9	4
	Calcium	16.0	19.5	60.5	127	156	4
	Magnesium	4.0	4.0	9.0	17.0	20.0	4
	Sodium	1,010	1,660	3,950	6,240	6,890	4
	Potassium	29.0	--	35.0	--	450	3
	Bicarbonate	988	1,240	1,680	1,990	2,130	4
	Chloride	1,100	1,680	5,350	8,930	9,420	4
	Sulfate	21.0	--	190	--	218	3
	Total dissolved solids	3,140	4,490	11,000	16,800	17,400	4
	Iron	37,000	--	--	--	--	1
Niobrara confining unit	pH (standard units)	6.1	6.9	7.2	7.9	8.6	42
	Calcium	10.0	37.0	78.5	234	5,110	42
	Magnesium	4.0	12.0	36.0	83.2	373	41
	Sodium	1,020	4,310	10,800	17,500	43,700	42
	Potassium	13.0	--	100	--	1,240	3
	Bicarbonate	146	584	774	1,010	1,840	42
	Carbonate	105	--	--	--	--	1
	Chloride	1,470	6,350	16,300	27,500	67,300	42
	Sulfate	1.0	20.0	25.0	42.5	322	28
	Total dissolved solids	3,550	11,600	27,200	46,600	112,000	42
	Iron	1,000	5,000	10,000	24,000	88,000	15
Frontier aquifer	pH (standard units)	5.6	6.2	6.6	7.3	9.1	11
	Calcium	15.0	404	1,030	5,560	16,800	11
	Magnesium	5.0	51.0	90.0	345	1,340	11
	Sodium	202	1,530	11,400	15,000	16,000	11
	Potassium	33.0	104	600	3,850	12,300	9
	Bicarbonate	153	451	573	803	2,440	11
	Carbonate	60.0	--	--	--	--	1
	Chloride	209	18,200	24,800	33,700	57,200	11
	Sulfate	5.0	8.0	13.0	61.0	97.0	6
	Total dissolved solids	691	27,000	41,200	60,800	91,600	11
	Iron	12,000	52,000	60,500	69,100	140,000	6

Appendix F6. Summary statistics for produced-water samples, Great Plains, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wall Creek Sandstone Member of the Frontier Formation	pH (standard units)	8.2	--	--	--	8.6	2
	Calcium	5.0	--	--	--	6.0	2
	Magnesium	1.0	--	--	--	1.0	2
	Sodium	1,410	--	--	--	1,430	2
	Potassium	6.0	--	--	--	7.0	2
	Bicarbonate	3,090	--	--	--	3,140	2
	Chloride	360	--	--	--	396	2
	Sulfate	62.0	--	--	--	--	1
	Total dissolved solids	3,340	--	--	--	3,410	2
Greenhorn confining unit	pH (standard units)	8.6	--	--	--	--	1
	Calcium	19.0	--	--	--	--	1
	Magnesium	2.0	--	--	--	--	1
	Sodium	766	--	--	--	--	1
	Potassium	10.0	--	--	--	--	1
	Bicarbonate	1,150	--	--	--	--	1
	Chloride	150	--	--	--	--	1
	Sulfate	387	--	--	--	--	1
	Total dissolved solids	2,010	--	--	--	--	1
Muddy Sandstone aquifer	pH (standard units)	5.7	7.5	8.0	8.4	9.1	31
	Calcium	8.0	23.0	48.0	139	194	31
	Magnesium	2.0	8.5	16.0	39.5	1,550	28
	Sodium	462	2,470	4,190	7,620	19,300	31
	Potassium	5.0	11.5	25.0	35.5	515	16
	Bicarbonate	403	854	1,090	1,500	2,210	31
	Carbonate	20.0	40.0	66.0	228	384	4
	Chloride	60.0	2,880	5,700	12,000	28,800	31
	Sulfate	25.0	29.0	128	511	8,820	21
	Total dissolved solids	1,240	6,920	11,000	20,500	50,300	31
	Iron	100	--	--	--	400	2
Cloverly aquifer	pH (standard units)	7.7	--	--	--	--	1
	Calcium	66.0	--	--	--	--	1
	Magnesium	24.0	--	--	--	--	1
	Sodium	3,470	--	--	--	--	1
	Potassium	31.0	--	--	--	--	1
	Bicarbonate	1,830	--	--	--	--	1
	Chloride	4,440	--	--	--	--	1
	Sulfate	92.0	--	--	--	--	1
	Total dissolved solids	9,030	--	--	--	--	1

Appendix F6. Summary statistics for produced-water samples, Great Plains, Wyoming.—Continued

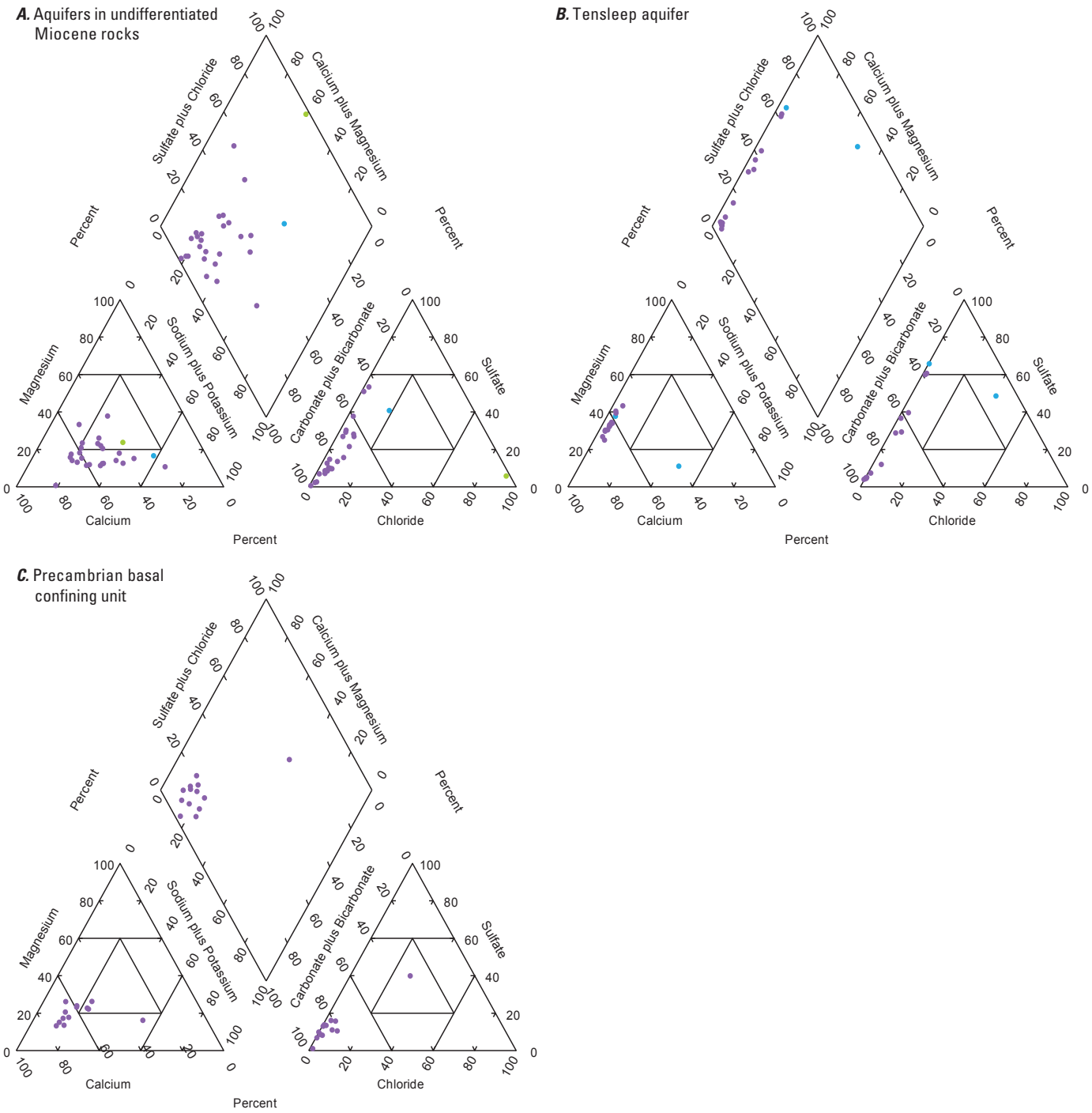
[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Consituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Sundance aquifer	pH (standard units)	8.2	--	--	--	8.6	2
	Calcium	51.0	--	--	--	64.0	2
	Magnesium	24.0	--	--	--	27.0	2
	Sodium	827	--	--	--	1,230	2
	Potassium	11.0	--	--	--	40.0	2
	Bicarbonate	586	--	--	--	915	2
	Chloride	140	--	--	--	370	2
	Sulfate	1,080	--	--	--	1,850	2
	Total dissolved solids	2,680	--	--	--	3,830	2
Casper aquifer	Calcium	592	--	--	--	--	1
	Magnesium	207	--	--	--	--	1
	Sodium	211	--	--	--	--	1
	Bicarbonate	150	--	--	--	--	1
	Chloride	105	--	--	--	--	1
	Sulfate	2,420	--	--	--	--	1
	Total dissolved solids	3,680	--	--	--	--	1
Hartville aquifer	pH (standard units)	7.2	--	7.9	--	8.1	3
	Calcium	222	--	322	--	770	3
	Magnesium	51.0	--	79.0	--	83.0	3
	Sodium	590	--	1,000	--	1,430	3
	Bicarbonate	183	--	296	--	854	3
	Chloride	54.0	--	106	--	361	3
	Sulfate	1,810	--	2,340	--	4,410	3
	Total dissolved solids	2,900	--	4,220	--	7,600	3

Appendix G

Trilinear Diagrams for Environmental Water Samples

Laura L. Hallberg, and Melanie L. Clark

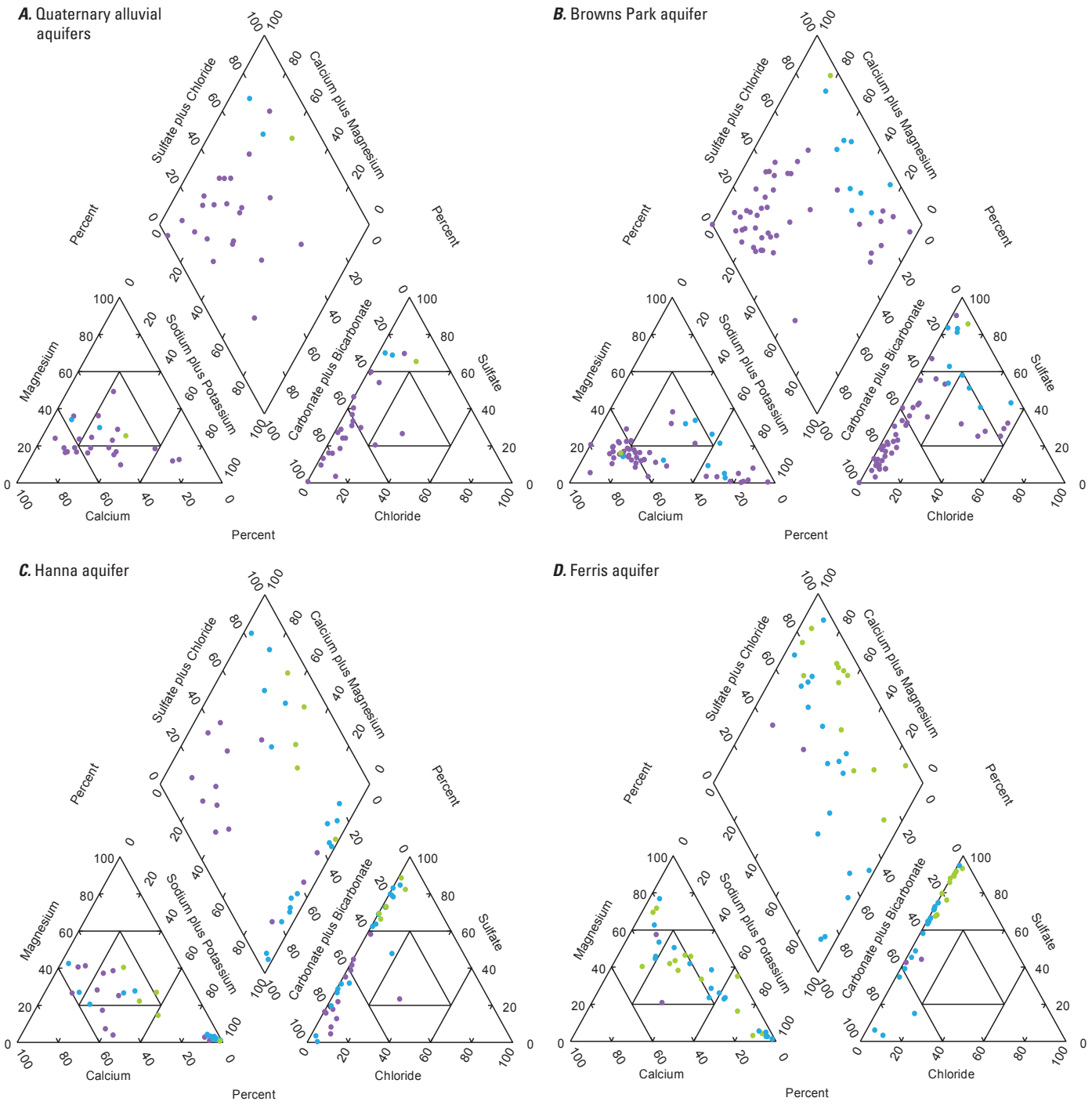


EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Sweetwater Arch.



EXPLANATION

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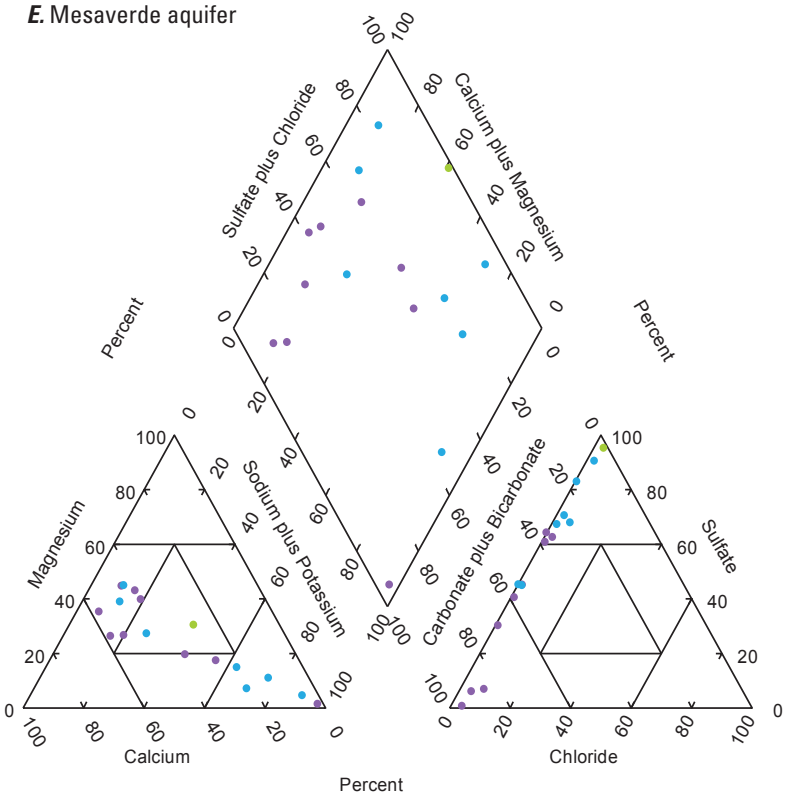
- Greater than or equal to 35,000; briny

Appendix G2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the central Wyoming basins (south).

E. Mesaverde aquifer



EXPLANATION

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- Less than or equal to 999; fresh
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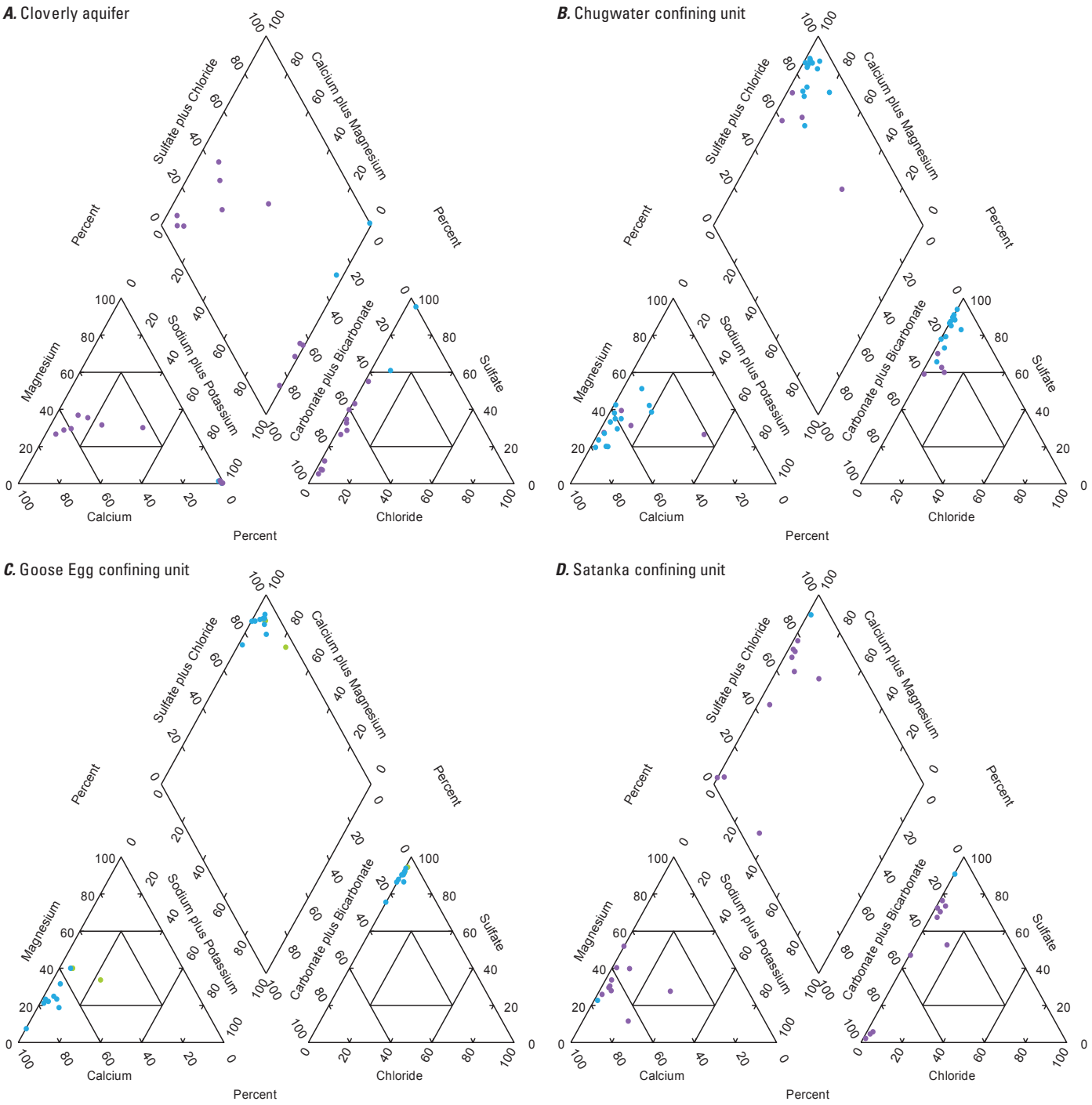
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the central Wyoming basins (south). —Continued



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

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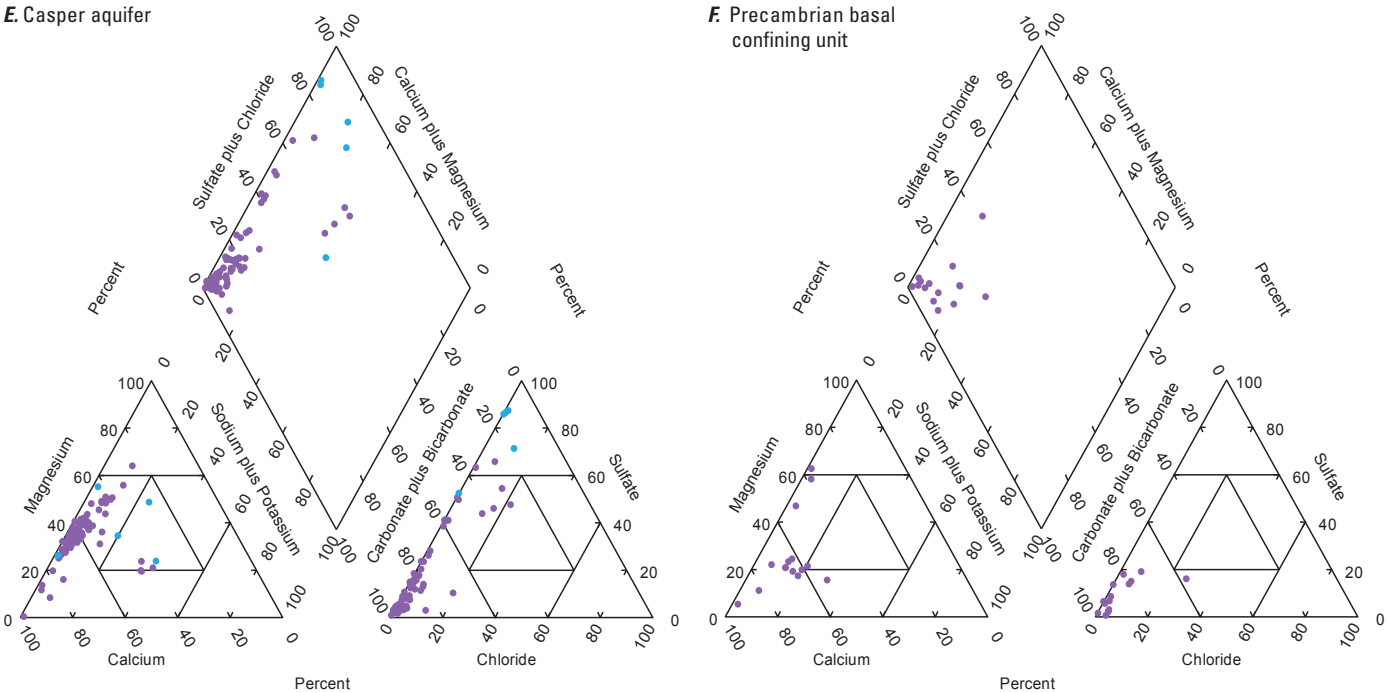
- Greater than or equal to 35,000; briny

Appendix G3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Laramie Mountains.

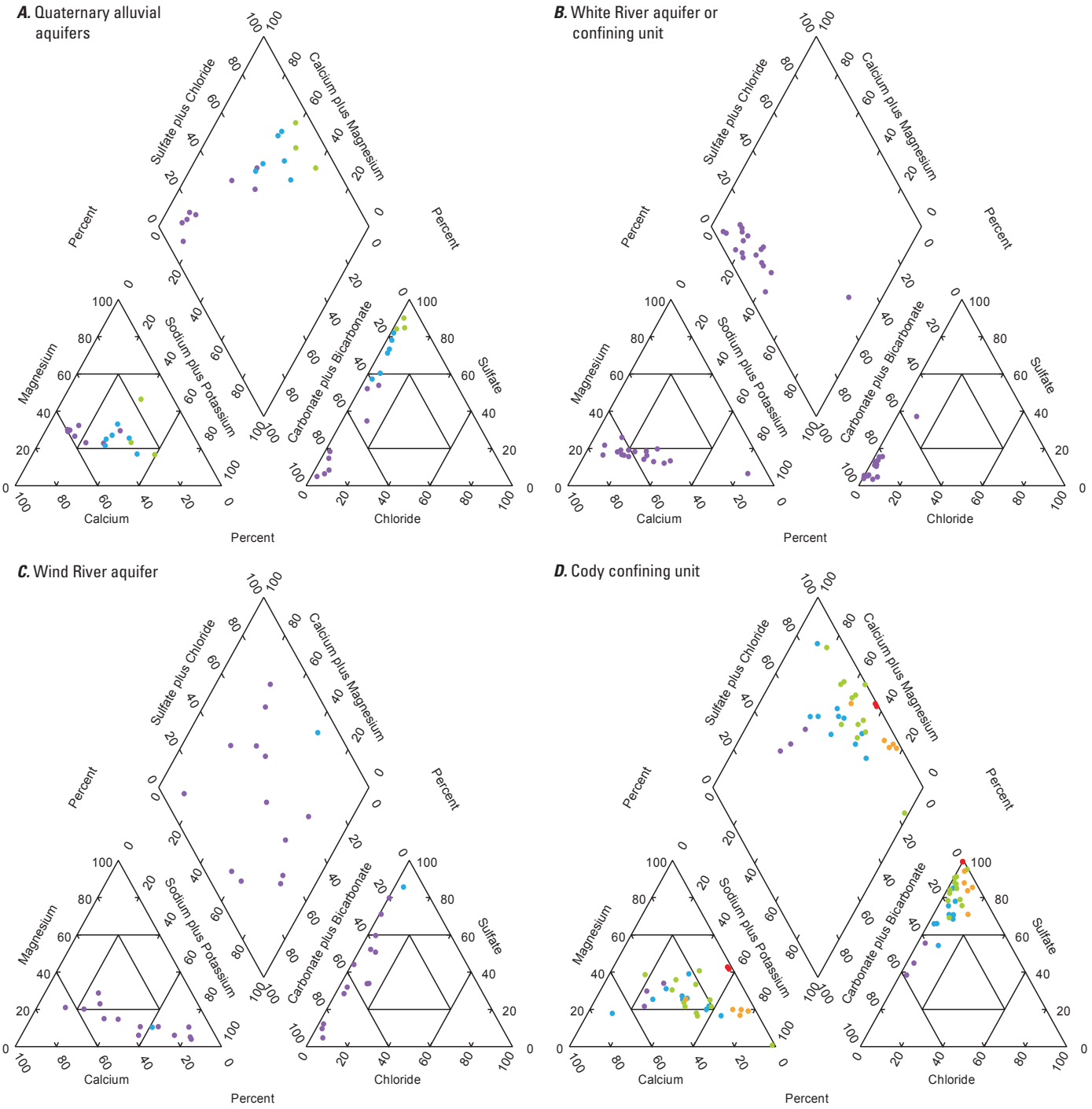


EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Laramie Mountains.—Continued

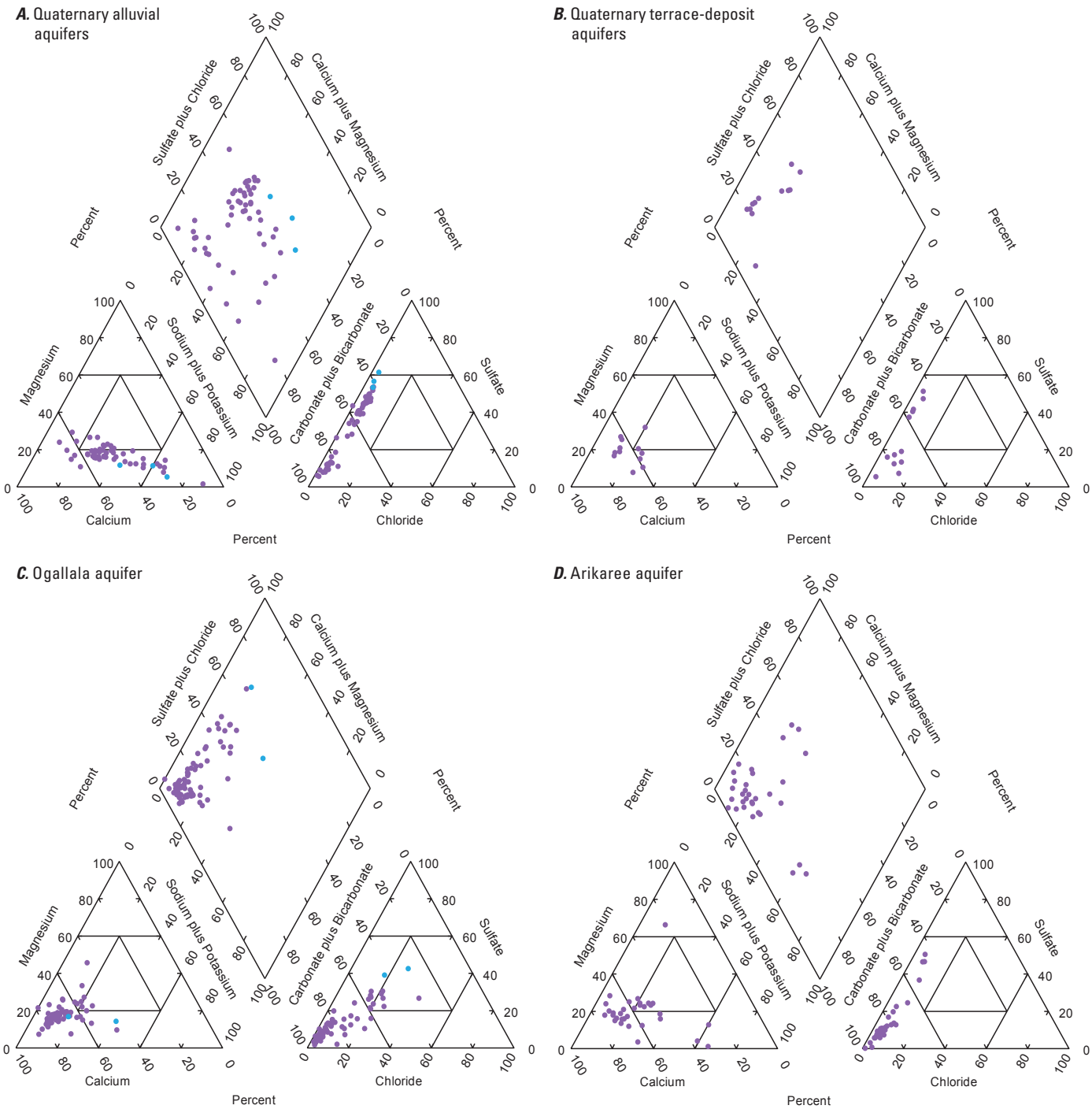


EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G4. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the central Wyoming basins (north).

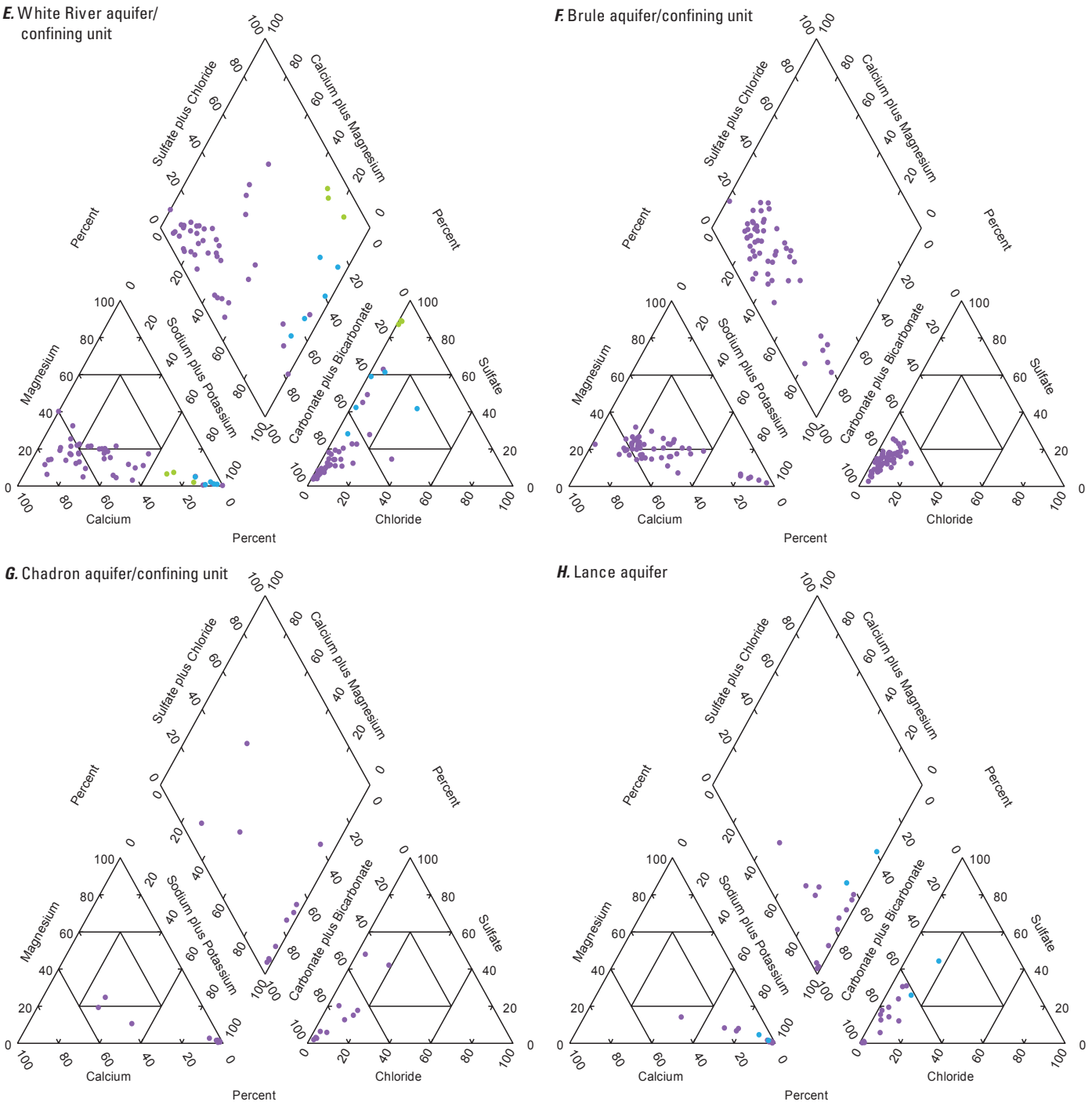


EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G5. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Great Plains.



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

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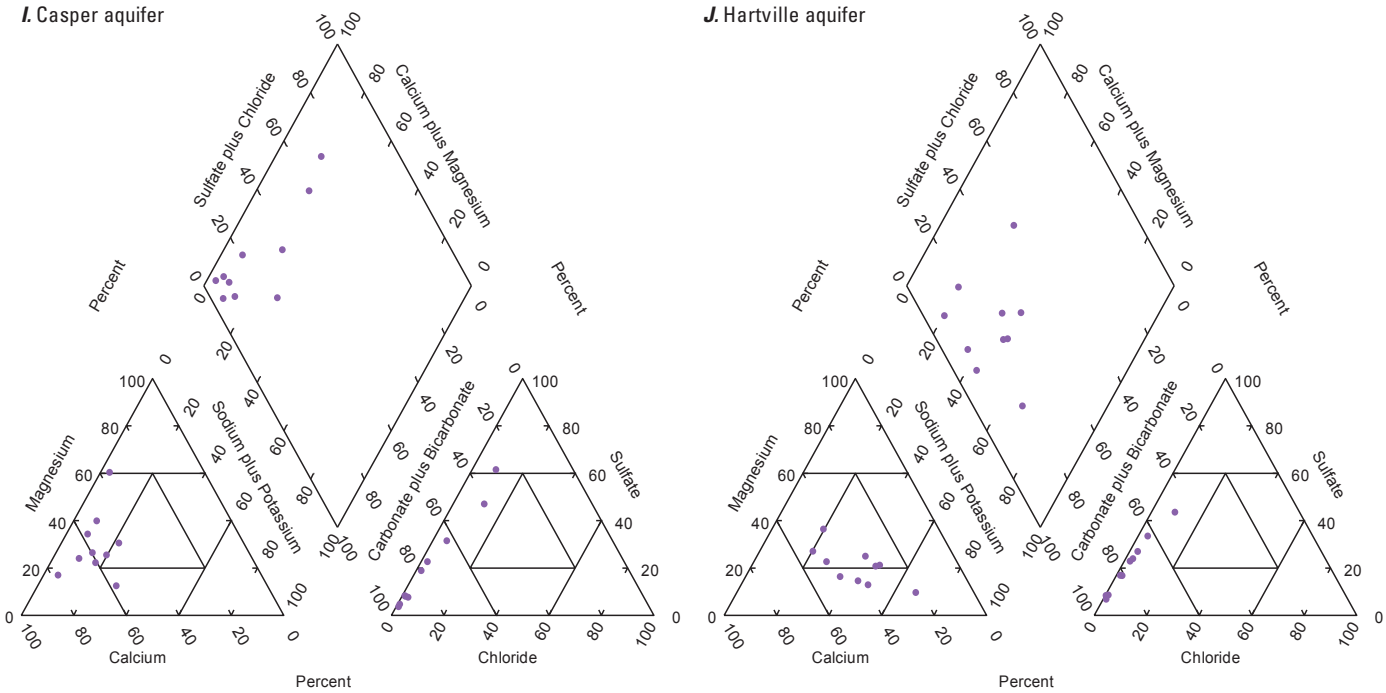
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G5. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Great Plains.—Continued



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

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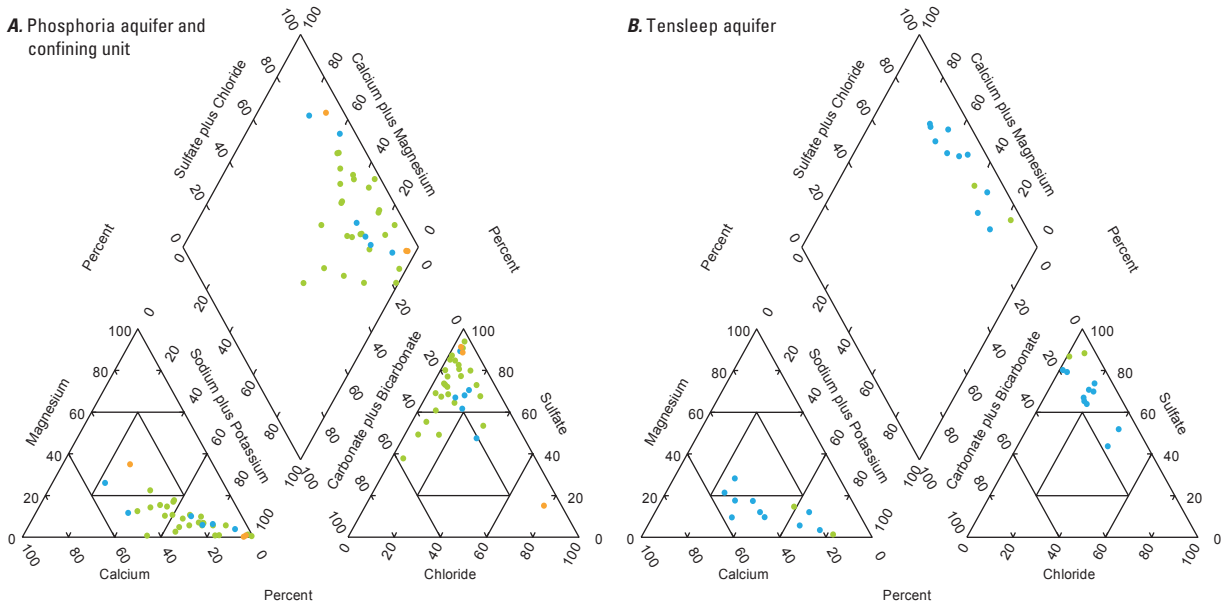
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G5. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples from the Great Plains.—Continued

Appendix H

Trilinear Diagrams for Produced Water Samples

Laura L. Hallberg, and Melanie L. Clark



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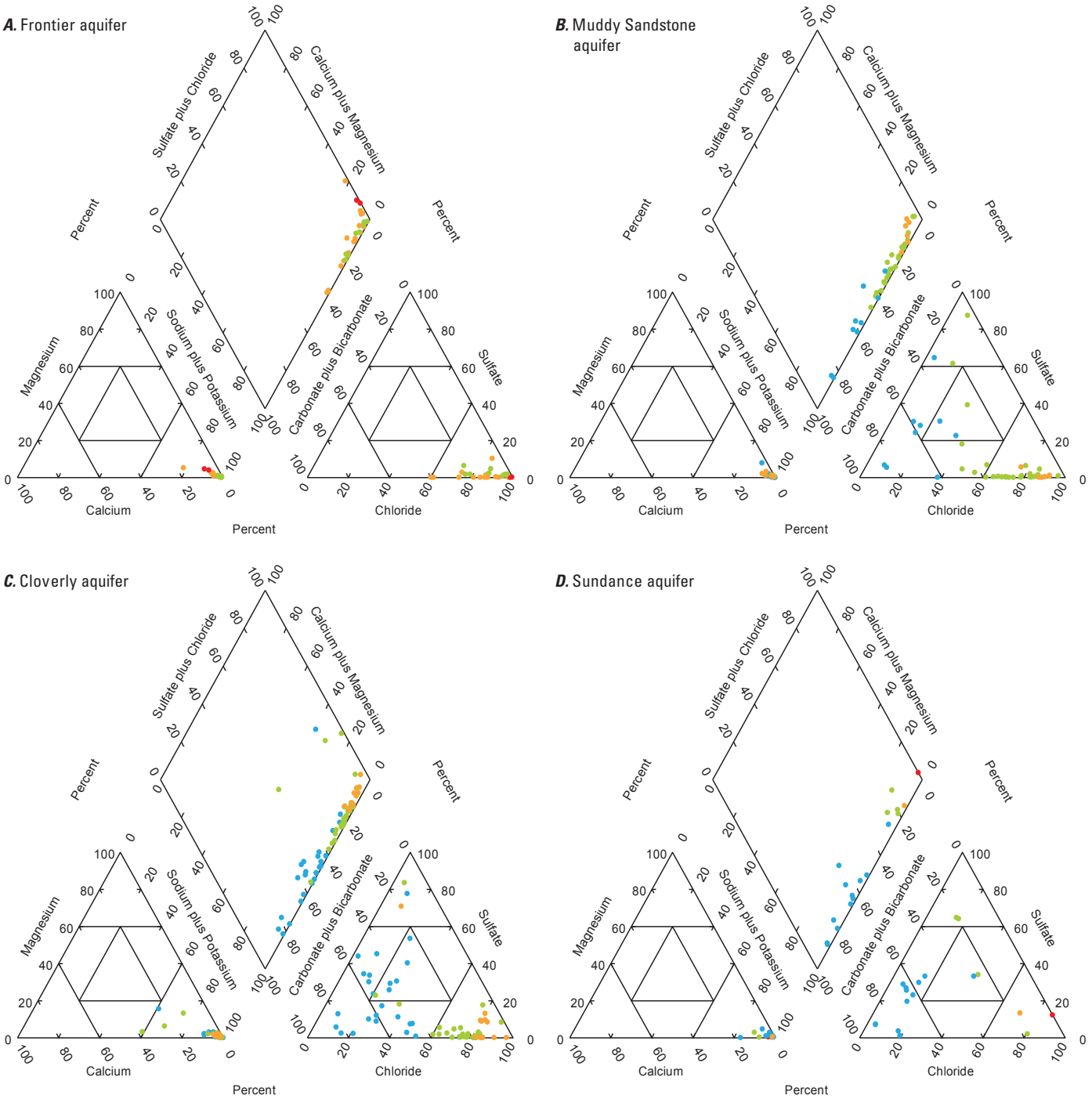
Appendix H1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the Sweetwater Arch.



EXPLANATION

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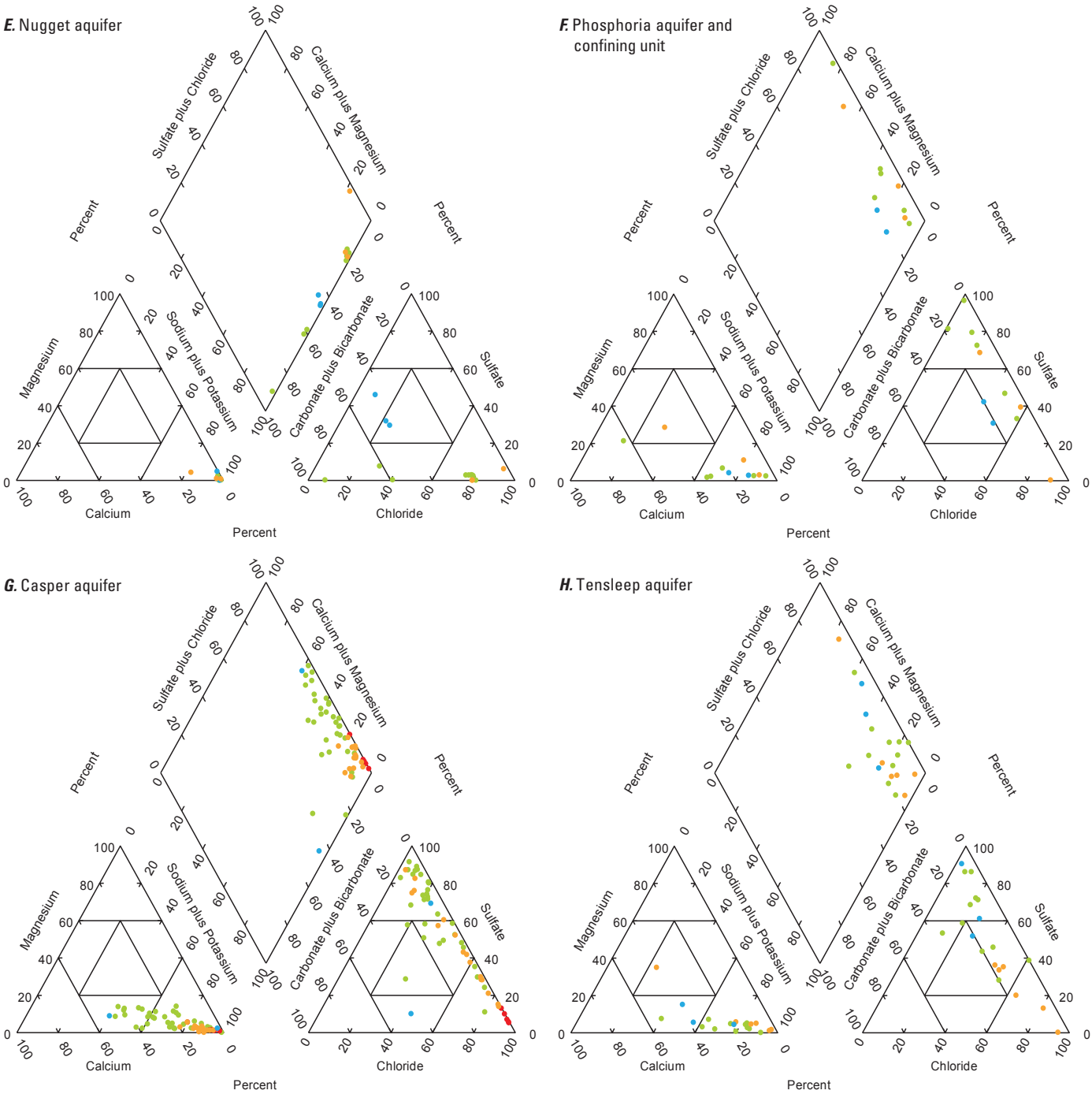
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the central Wyoming basins (south).



EXPLANATION

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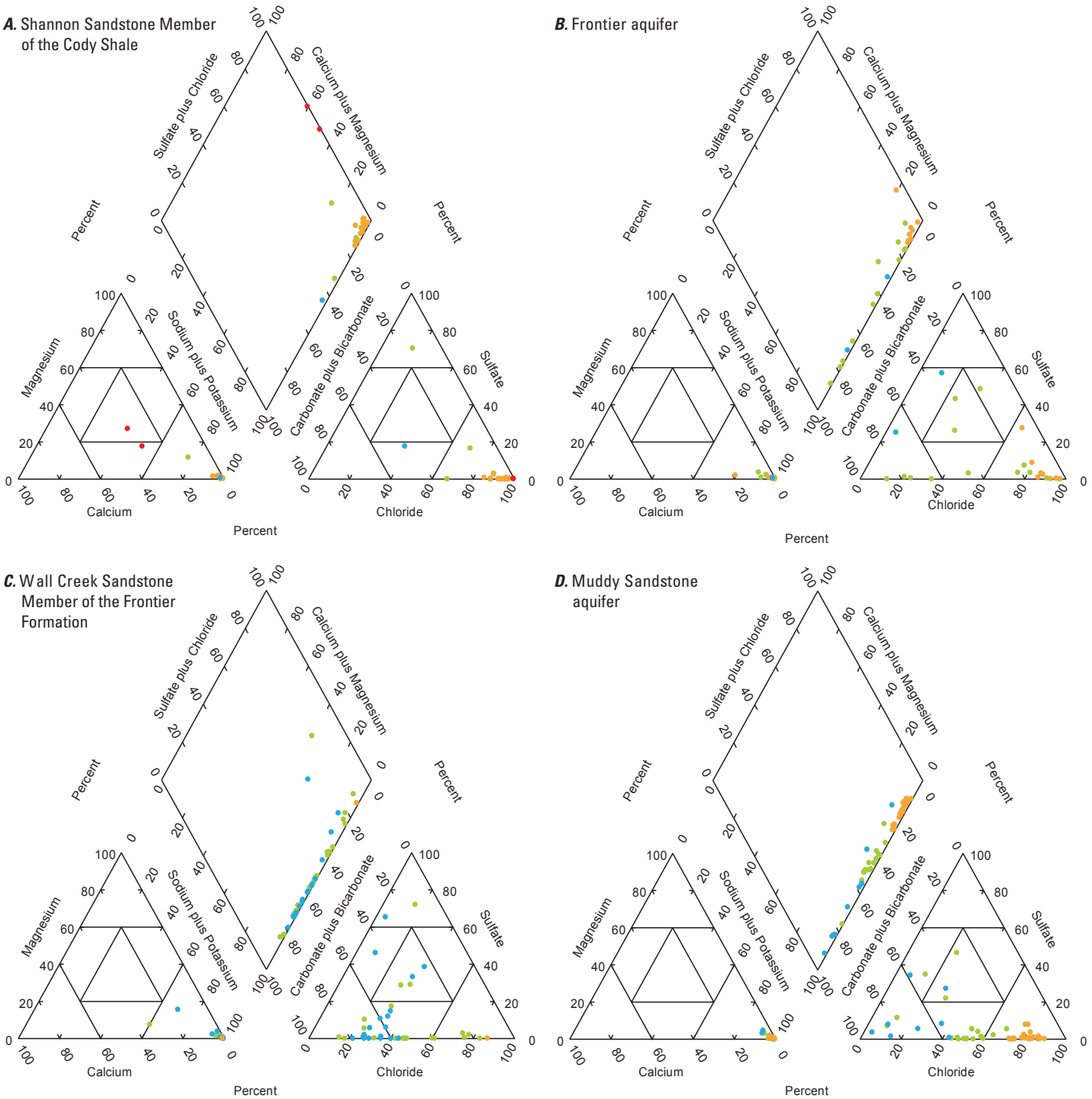
Appendix H2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the central Wyoming basins (south).—Continued



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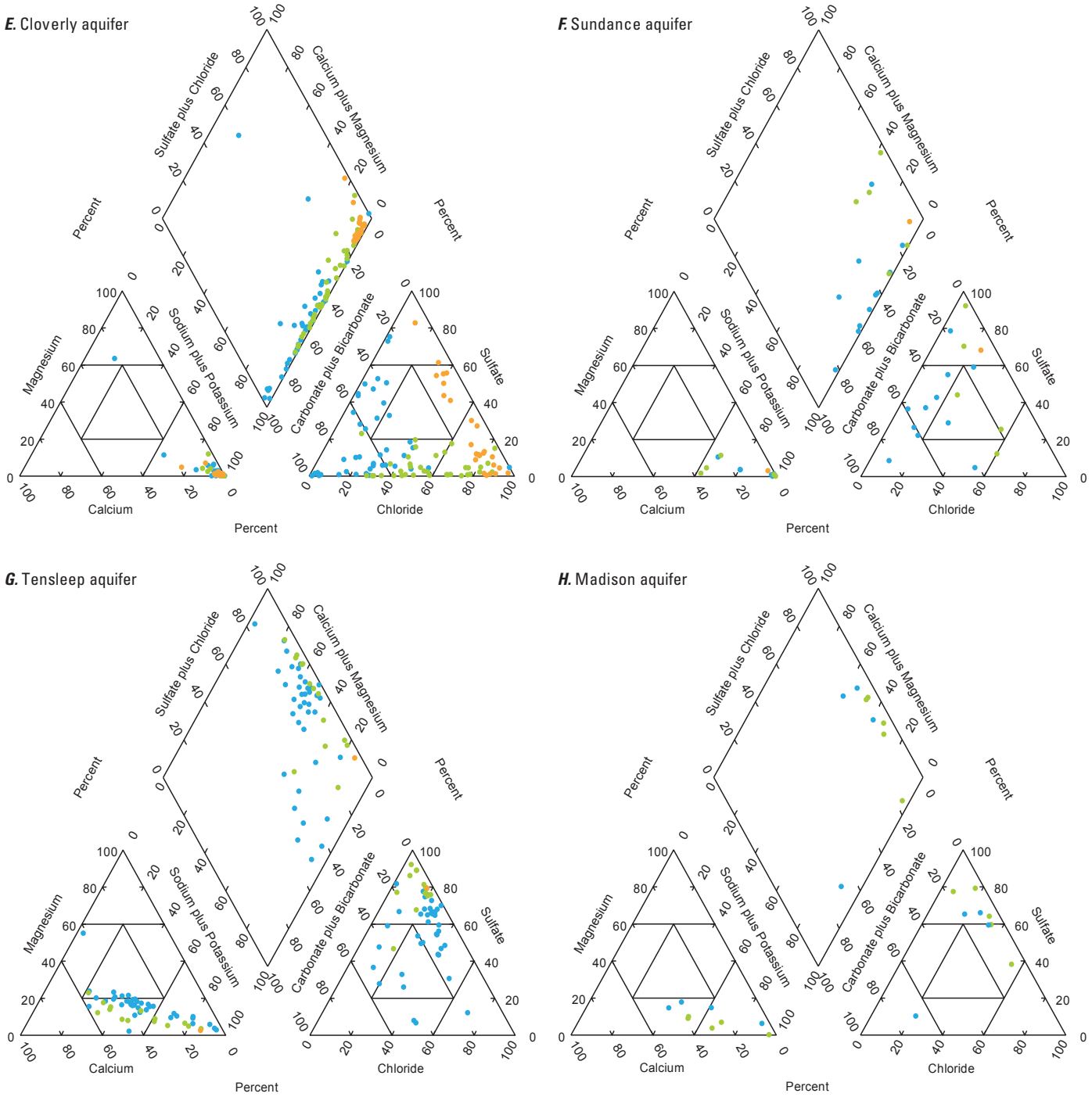
Appendix H3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from central Wyoming basins (north).



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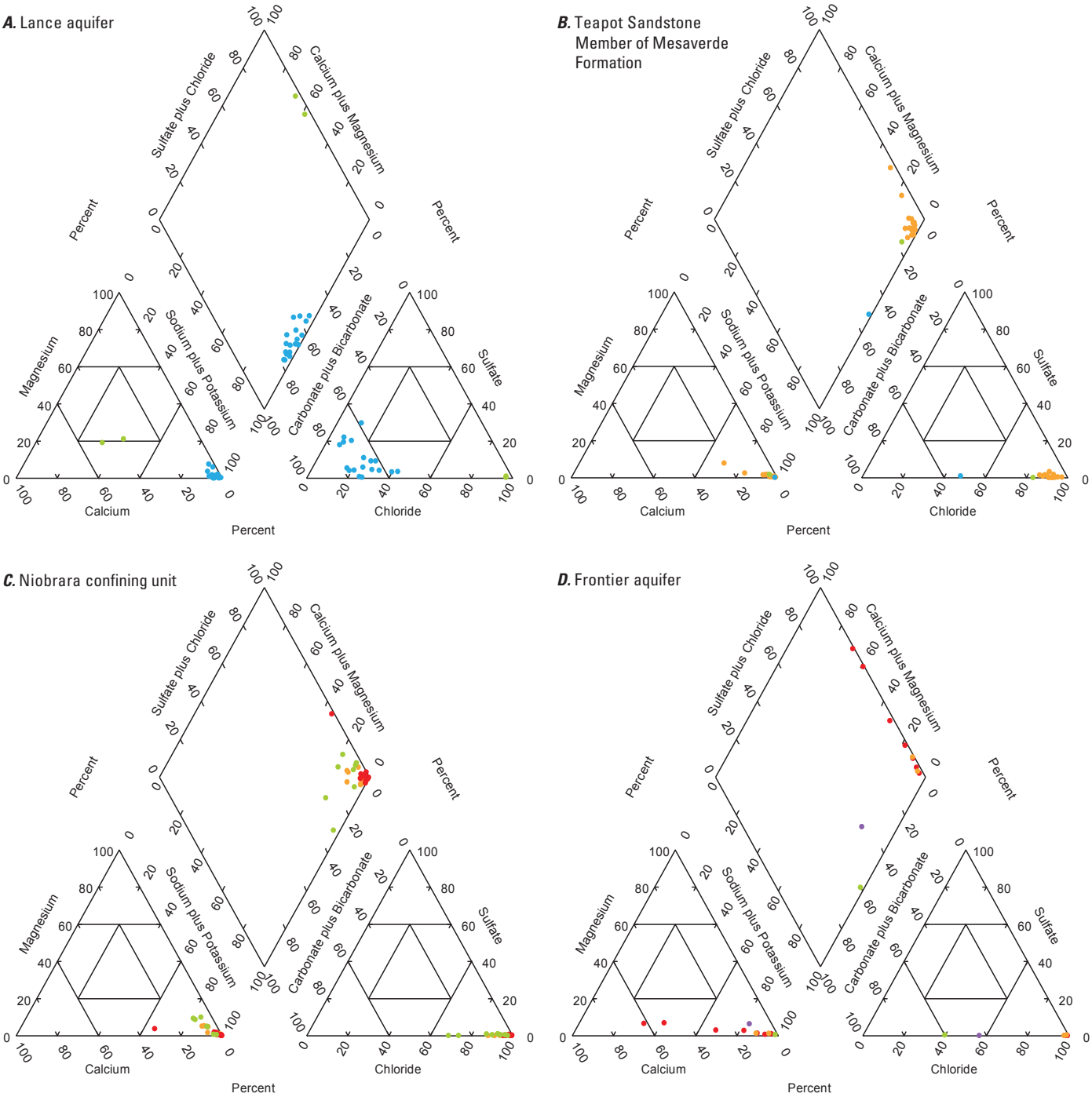
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the central Wyoming basins (north).—Continued



EXPLANATION

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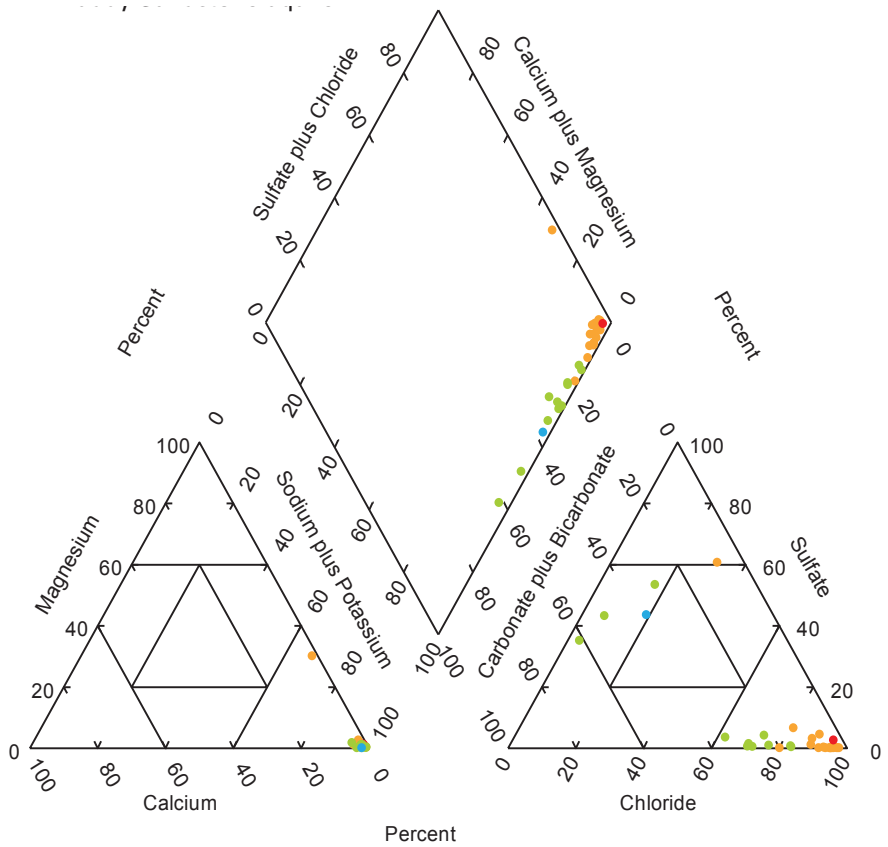
Appendix H4. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the Great Plains.



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Appendix H4. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples from the Great Plains.—Continued

Interpreting the past – providing for the future