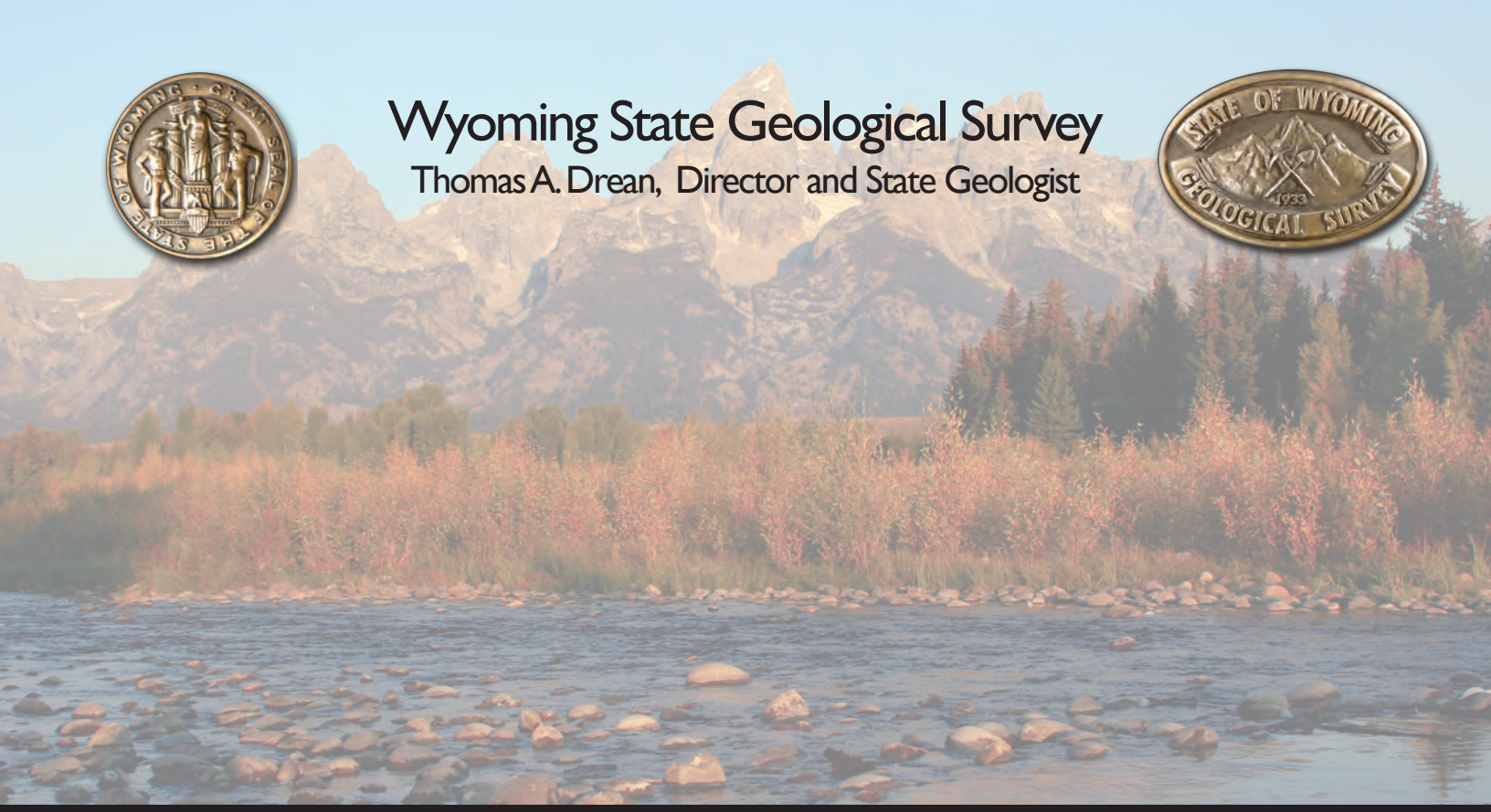


Wyoming State Geological Survey
Thomas A. Drean, Director and State Geologist

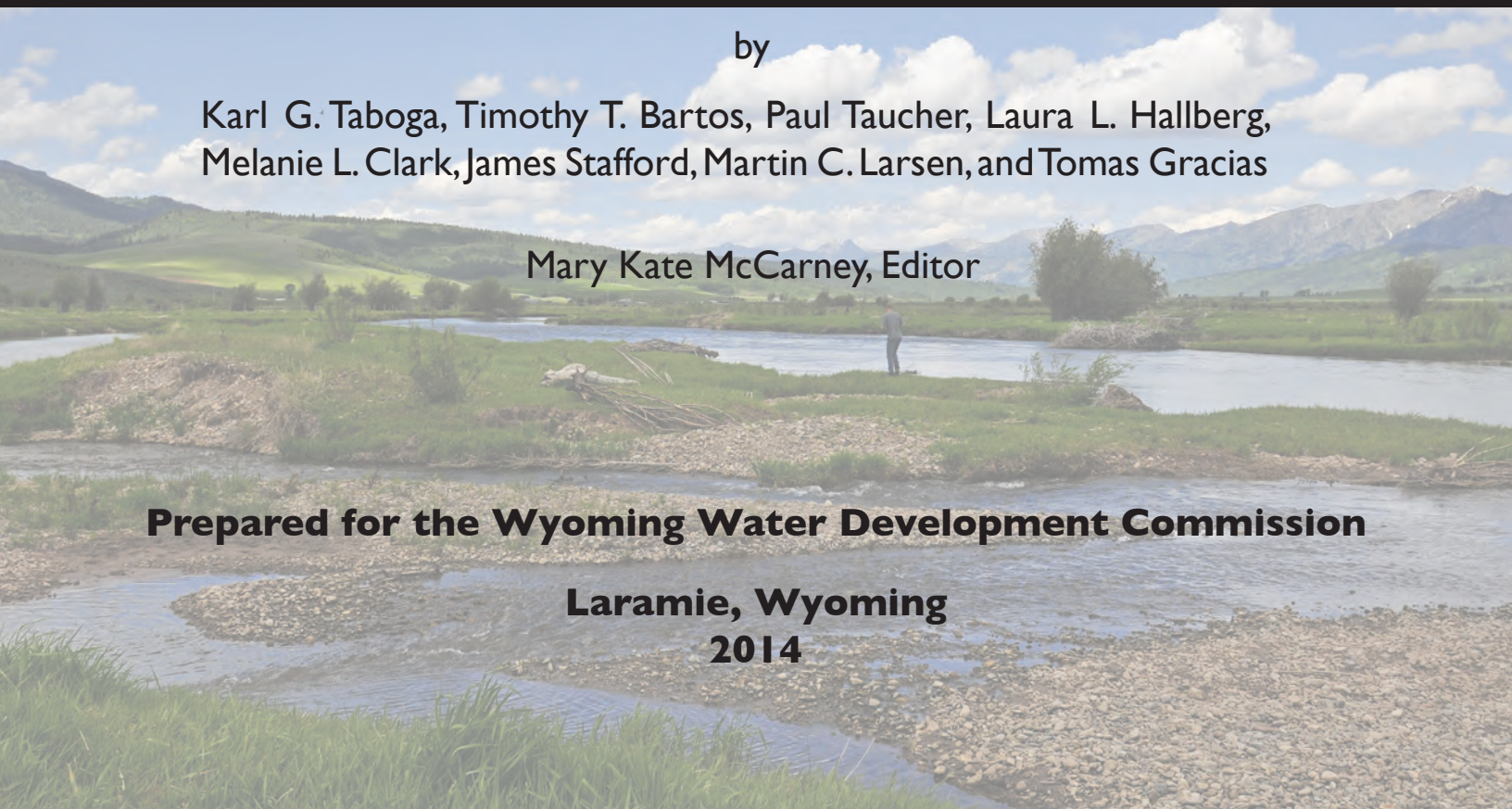
Snake/Salt River Basin Water Plan Update Groundwater Study

Available Groundwater Determination Technical Memorandum No. 7

by

Karl G. Taboga, Timothy T. Bartos, Paul Taucher, Laura L. Hallberg, Melanie L. Clark, James Stafford, Martin C. Larsen, and Tomas Gracias

Mary Kate McCarney, Editor



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Snake/Salt River Basin Water Plan Update
Groundwater Study
Level 1 (2011-2014)

Available Groundwater Determination
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Cover: Upper Snake River with Teton Range. Photo by Seth Wittke, WSGS. Lower Salt River, near Etna, Wyoming. Photo by Tony Bergantino, WRDS.

Available Groundwater Determination

Technical Memorandum No. 7

WWDC Snake/Salt River Basin Water Plan Update
Groundwater Study
Level 1 (2011 – 2014)

June 2014

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Mary Kate McCarney, Editor

This report was prepared under contract for the Wyoming Water Development Commission (WWDC) 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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Chapter 1

Introduction

Karl Taboga and Paul Taucher

The Wyoming State Engineer's Office (SEO) published the first State Framework Water Plan in 1973 under the Wyoming Water Planning Program. The publication presented a water resources 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 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 feasibility study, in collaboration with the University of Wyoming (UW) and the SEO, which included public input and compilation of a statewide water inventory. Based on the feasibility study, the Wyoming Legislature accepted the recommended planning framework to update the original 1973 State Framework Water Plan and funded the State Water Planning Process in 1999, 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
- direct water resource planning for the state of Wyoming for a 30-year timeframe.
- The Wyoming Framework Water Plan (WWC Engineering and others, 2007) summarized the separate water plans for Wyoming's seven major river basins **(fig. 1-1)** completed between 2001 and 2006.

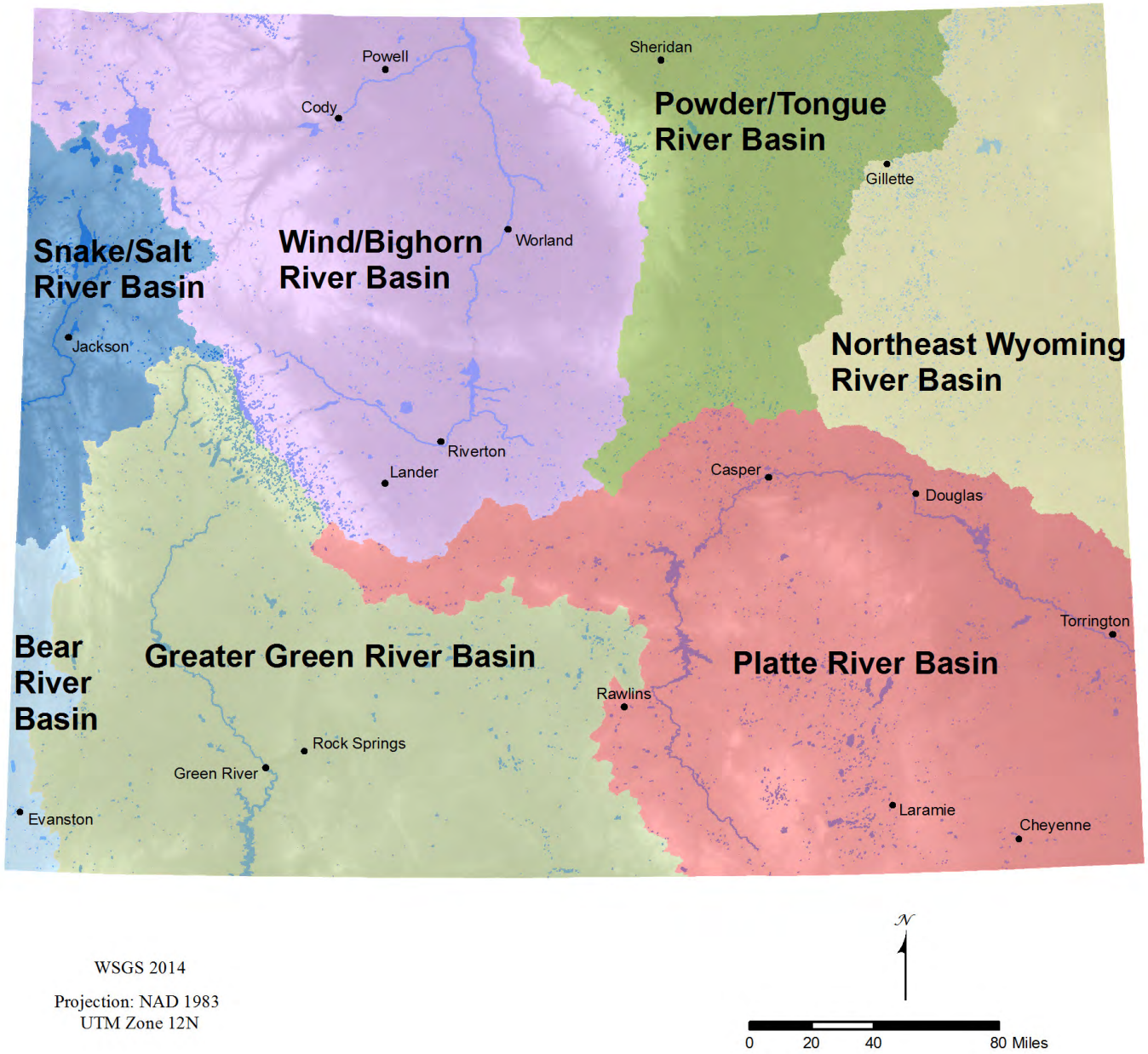
Technical Memorandum S of the previous Snake/Salt River Basin Water Plan (Sunrise Engineering and others, 2003) contains a groundwater resource investigation that thoroughly examines the basin's resources and usage. This Available Groundwater Determination represents the most current assessment of the groundwater resources in the Snake/Salt River Basin, updating and expanding the information presented in the 2003 groundwater investigation. The data contained in this memorandum are a compilation of existing information 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 research was conducted for this memorandum.

The format of this update follows the general layout of other, recent groundwater determinations co-authored by the Wyoming State Geological Survey (WSGS) and U.S. Geological Survey (USGS) for the Green River Basin (2010), the Wind/Bighorn River Basin (2012), the Platte River Basin (2013), and the Bear River Basin (2014); this memorandum incorporates much of the content of these four previous studies, frequently without citation.

1.1 Interagency Agreement and scope

The WWDC and WSGS entered into an Interagency Agreement in September 2011 to update the groundwater information contained in the previous Snake/Salt River Basin water plan (Sunrise Engineering and others, 2003). The previous Snake/Salt River Water Plan is available on the WWDC website at http://waterplan.state.wy.us/plan/snake/snake-plan.html. The agreement outlined the following tasks to update the previous Snake/Salt River Basin water plans:

- **Identify the major (i.e., most widely used) aquifers in the Snake/Salt River Basin:** To make this determination, the USGS defined all aquifers and confining units in the Snake/Salt River Basin and presented the information on hydrostratigraphic nomenclature charts (**pls. 4**, **5**, and **6**). Based on these detailed analyses, the Geographic Information System (GIS) geologic units mapped on **plate 1** and described in **appendix A** were organized into a comprehensive hydrostratigraphic chart and surface hydrogeology map for the Snake/Salt River Basin (**pl. 2**). In some cases, two or more minor aquifers that are hydrologically connected are grouped and treated as a single combined hydrogeologic unit. The general



WSGS 2014

Projection: NAD 1983
UTM Zone 12N

Figure 1-1. Major drainage basins, Wyoming.

geology of the Snake/Salt River Basin is discussed in **chapter 4** and individual aquifers are detailed in **chapter 7**.

- **Define the three-dimensional extent of the aquifers:**
  Plate 2 is a map of the outcrop areas for the Snake/Salt River Basin's aquifers and confining units. Six cross sections (**figs. 4-2** through **4-7**) illustrate the subsurface configuration of the geologic units that constitute the hydrogeologic units at selected locales within the basin. Isopach maps with substantial coverage of the major aquifers in the Snake/Salt River Basin are not available at this time.

- **Describe the following hydraulic, hydrogeologic, and hydrogeochemical properties of the aquifers and confining units:**
  - Physical characteristics – **chapters 4** and **7** discuss 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 E** and **F.**
  - Principal potential pollutants - **chapter 5** contains a discussion of potential pollution sources. 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 basinwide, aquifer-specific assessment of groundwater quantity is not available. The complex geology of the Snake/Salt River Basin does not lend itself to the general assumptions about aquifer properties, geometry, and saturated thickness that a plausible estimate of total and producible groundwater resources requires. The most important aquifers in the Snake/Salt River Basin, including the Snake/Salt River Alluvium and the Salt Lake, Teewinot, and Wind River formations, have been described in numerous, specific studies (**appendix B**) 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 Snake/Salt River Basin. Maps depicting the outcrop areas used to calculate the annual rate of recharge for specific aquifers and groups of aquifers throughout the Snake/Salt River Basin are provided in **figures 6-1 – 6-6**. **Section 5.1** and **chapter 6** discuss recharge.

- **Estimate aquifer recharge rates:**
  Existing maps depicting average annual precipitation (**fig. 3-3**) and estimated recharge rates (**fig. 5-2**) over the entire Snake/Salt River Basin were adapted for presentation in this technical memorandum. Existing annual recharge rates were multiplied by aquifer outcrop areas (**figs. 6-1** through **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 Snake/Salt River Basin.

- **Estimate the "safe yield" potential for the aquifers and describe implications of hydrologically connected groundwater and surface water:**
  The concept of "safe yield" is discussed in **section 5.1.4**. This report provides estimates of total recharge (average annual) for the Snake/Salt River Basin in **chapter 6** and compares these recharge estimates to current groundwater withdrawals in **chapter 8**.

- **Describe and evaluate existing groundwater studies and models:**
  Existing groundwater models are identified and evaluated, and recommendations for future groundwater modeling in the Snake/Salt River Basin are discussed in **chapter 7.**

- **Identify future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands:**
  Several approaches to address future groundwater development potential are discussed throughout this report.
  - General and aquifer-specific hydrogeology relative to groundwater development potential is discussed in **chapters 5** and **7**.
  - **Figures 8-1** through **8-7** show wells permitted by the SEO in the Snake/Salt River Basin through February 27, 2012. These figures include 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, 2003 through February 27, 2012, shown on inset tables contained within these figures, illustrate the focus of recent groundwater development efforts. Existing groundwater development in the Snake/Salt River Basin is discussed in **chapters 7** and **8**.
  - A summary of groundwater development studies and projects in the Snake/Salt 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 studies, is described in **chapter 7**.
  - Groundwater development prospects identified in the groundwater resource investigations of the previous Snake/Salt River Basin Water Plan (Sunrise Engineering and others, 2003) are discussed in **chapter 9**.
  - Current WWDC and SEO projects related to groundwater development in the Snake/Salt 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 SEO and the Wyoming Department of Environmental Quality (WDEQ) contributed significant datasets for developing some of the figures presented in this technical memorandum.

- The WWDO and WRDS provided the WSGS with overall program guidance and standards, software, and format requirements for deliverables (e.g., maps, databases, metadata, tables, and graphs).
- WSGS was the primary compiler of the information developed in **chapters 1** through **6** and **chapters 8**, and **9**.
- The USGS, under contract to the WSGS, compiled the information used in **chapter 7** and **section 5.6.1**.
- The WSGS and USGS cooperated on sections of **chapters 5** and **9**.
- On behalf of WWDC/WWDO, the WRDS will feature the associated deliverables on its website at http://www.wrds.uwyo.edu/.

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

The WSGS is a separate operating agency under the executive branch of state government (Wyoming State Statutes 9-2-801 and 9-2-803 through 9-2-810). The WSGS's purposes are 1) to study, examine, and understand the geology, mineral resources, and physical features of the state; 2) to prepare, publish, and distribute (free or for a nominal price) reports and maps of the state's geology, mineral resources, and physical features; and 3) to provide information, advice, and services related to the geology, mineral resources, and physical features of the state. The survey'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. WSGS hydrogeologists conduct research; compile data; create and distribute maps and reports; and address inquiries to assist citizens, industry, and state and federal agencies in planning, decision making, and analysis of water issues.

The USGS provides data, maps, reports, and other scientific information to help individuals and local and state governments manage, develop, and protect the United States' 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." Toward these goals, the USGS employs experienced scientists and support staff from a wide range of 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 SEO and WWDO cooperate on many projects. SEO personnel attend meetings on river basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the SEO and WDEQ (K. Clarey, WWDO, 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, during periods of limited supply, the first party to put a source of water to beneficial use has a "priority" water-right honored prior to those of other, later users. An exception is that municipalities can obtain water-rights from earlier priority uses through eminent domain (Wyoming State Statutes 1-26). The Wyoming Constitution establishes that all natural waters are property of the state. Therefore, 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 takes precedence over other uses. In Wyoming, water-rights are attached to the land and 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, a panel comprised of the superintendents of the four state water divisions and the state engineer. The entire Snake/Salt River Basin area is included in SEO Water Division IV. A comprehensive discussion of the laws that govern Wyoming water resources is provided online at: http://seo.state.wy.us/PDF/b849r.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 and contamination. 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 [sic] 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 [sic]."

"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). Prior to the 1969 amendment, domestic and stock wells were exempt from the requirement to obtain a permit and held a preferred right over other wells. The 1969 amendment established priorities for domestic and stock wells similar to those for other wells. The Groundwater Division [of the SEO] 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

Surface water resources of Wyoming are subject to interstate agreements that limit how much streamflow can be depleted before leaving the state. Furthermore, conflicts among users within the state or across state lines can occur where groundwater extraction may affect surface flows. Although interconnection between groundwater and surface water is not currently a significant water-rights issue in the Snake/Salt River Basin, it could become a point of contention in the future as the basin's population grows.

To avert conflicts over the allocation and use of surface water flows within the Snake/Salt River Basin, the states of Idaho and Wyoming agreed to the Snake River Compact in 1949. The Compact allocates 4 percent of the waters of the Snake River to Wyoming and 96 percent to Idaho exclusive of established Wyoming water rights (prior to the date of signing) for direct diversion or storage. Unlike the Bear and Platte River Basins, the Compact considers surface flows only and does not place any regulation on the allocation and development of groundwater. The Snake River Compact is available for review at: https://sites.google.com/a/wyo.gov/seo/interstate-streams.

The basin area, examined in this report, consists of the Wyoming portion of the Snake and Salt River Basins and tributary areas in Idaho and Yellowstone National Park (**fig. 3-1**).

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 about Wyoming's public drinking water systems is available on the EPA Wyoming Drinking Water website:
http://www.epa.gov/safewater/dwinfo/wy.html

Except on the Wind River Indian Reservation, the WDEQ enforces groundwater quality regulations under the Wyoming Environmental Quality Act, with guidance from the Wyoming Environmental Quality Council. The WDEQ 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 WDEQ. The WOGCC has jurisdiction over Class II underground injection

wells (**chapter 5**) dedicated to disposal of produced water from state and federal oil and gas leases.

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 diversions, 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 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, WWDO, 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
- 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

1.4 Authorship

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area. WDEQ contributed several data sets that are presented on the potential aquifer contaminant figures. Special thanks are expressed to Chad Kopplin, Ben Way, Jerry Breed, Adrienne Nunn, Bill DiRienzo, Marica Murdock, Jonathan Deutscher, Cindi Martinez, Matthew Kunze, Nancy Nuttbrock, Bonnie Pierce, and Kim Medina at the WDEQ. Chris Nicholson and Tony Bergantino at WRDS helped obtain data and access reports from their library. Mary Kate McCarney provided technical review of the report. Jeff Hammerlink from the Wyoming Geographic Information Science Center (WyGisc) provided the data used to describe aquifer sensitivity and recharge.

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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

Karl Taboga and Paul Taucher

A variety of available information was reviewed and compiled for this updated and expanded study of the Snake/Salt River Basin groundwater resources. The updated data were obtained from regional and area-specific studies conducted by state and federal agencies in Wyoming and Idaho. This chapter discusses the data sources, approach, organization, and computer-based mapping used in this study and compares them to the previous Groundwater Resource Investigations contained within the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering and others, 2003).

The 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering and others, 2003) and associated technical memoranda constitute one of the earlier studies for Wyoming's seven major drainage basins completed by the Wyoming Water Development Commission (WWDC) between 2000 and 2011. The 2003 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 2003 Snake/Salt River Basin plan (Sunrise Engineering and others, 2003) and 2007 Wyoming Framework Water Plan (WWC and others, 2007) are cited frequently in this study, and where appropriate, links are provided to online information.

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
	University of Wyoming Libraries
WRDS	University of Wyoming Water Resources Data System
WDEQ	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	State Engineer's Office (Wyoming)
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 management studies have been previously conducted for areas contained wholly or partly within the Snake/Salt River Basin. The geographic scale of the earlier projects varies considerably. This study builds on these previous compilations. The primary hydrogeologic studies and associated supporting geologic investigations of the basin area are listed below in approximate chronologic order by agency and author(s):

- *U.S. Geological Survey Hydrologic Investigation Atlases*

  1968 – Whitcomb, H.A and Lowry, M.E., 1968, Groundwater resources and geology of the Wind River Basin area, central Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-270, map scale 1:250,000, 2 sheets.

  1975 – Lines, G.C., and Glass, W.R., 1975, Water resources of the Thrust Belt of western Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-539, map scale 1:250,000, 3 sheets.

  1976 – Cox, E.R., 1976, Water resources of northwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-558, map scale 1:250,000, 3 sheets.

  1994 – Whitehead, R.L., 1994 Groundwater

atlas of the United States, Segment 7, Idaho, Oregon, Washington: U.S. Geologic Survey Hydrologic Investigations Atlas HA-730-H, 31 p.

1996 – Whitehead, R.L., 1996 Groundwater 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, Groundwater reconnaissance study of the State of Wyoming, Introduction and seven basin reports: Prepared for Wyoming Natural Resource Board, Cheyenne, Wyoming, 355 p.

1981 – Ahern, J., Collentine, M., and Cooks, S., 1981, Occurrence and characteristics of ground water in the Green River Basin and Overthrust Belt, Wyoming: Report to U.S. Environmental Protection Agency, contract number G-008269-79, by Water Resources Research Institute, Laramie, Wyoming, 123 p.

1985 – Sando, S.K., Borrelli, John, and Brosz, D.J., 1985, Hydrologic impacts on the Salt River due to changes in irrigation systems: Wyoming Water Research Center, Water Resource Publication 85–16, 73 p.

1990 – Blanchard, M.R., Drever, J.I., and Huntoon, P.W., 1990, Discrimination between flow-through and pulse-through components of an alpine carbonate aquifer, Salt River Range, Wyoming: Wyoming Water Research Center, Water Resource Publication 90–31, 77 p.

- *Wyoming State Geological Survey publications*

1993 – Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., 1993, Stratigraphic chart showing the Phanerozoic nomenclature for the state of Wyoming: Geological Survey of Wyoming Map Series MS-41, no scale, 1 sheet.

Royse, F., Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho: *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., Eds., Geology of Wyoming: Laramie, Wyoming, Geological Survey of Wyoming Memoir No. 5, p. 272-311.

- *U.S. Geological Survey Water Supply Papers, Professional Papers, Scientific Investigation Reports, Scientific Investigation Maps, Water Resource Investigations Open-File Reports, Water Resource Investigations Reports, and Circulars.*

1951 – Love, J.D., Keefer, W.R., Duncan, D.C., Gergquist, H.R., Hose, R.K., 1951, Geologic map of the Spread Creek-Gros Ventre River area, Teton County, Wyoming: U.S. Geological Survey Oil and Gas Investigation Map, map scale 1:48,000, 1 map.

1961 – Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1961, Age of the Evanston Formation, western Wyoming: U.S. Geological Survey Professional Paper 424-B *in* Short papers in the geologic and hydrologic sciences, Article 64, p. B153-B154.

Gardner, L.S., 1961, Preliminary geologic map, columnar sections, and trench sections of the Irwin quadrangle, Caribou and Bonneville counties, Idaho, and Lincoln and Teton counties, Wyoming: U.S. Geological Survey Open-File Report

OF-61-53, map scale 1:48,000, 4 plates.

1964 – Lowry, M.E., and Gordon, E.D., 1964, Ground-water investigations in Yellowstone National Park, October 1960 to October 1963: U.S. Geological Survey Open-File Report 64–105, 39 p.

McGreevy, L.J., and Gordon, E.D., 1964, Ground water east of Jackson Lake, Grand Teton National Park, Wyoming: U.S. Geological Survey Circular 494, 27 p., 1 pl.

1965 – Albee, H.F., 1965, Preliminary geologic map of the Poker Peak and Palisades Reservoir quadrangles, Bonneville County, Idaho and Lincoln County, Wyoming: U.S. Geological Survey Open-File Report OF-65-2, map scale 1:24,000, 1 plate.

Jobin, D.A., 1965, Preliminary geologic map of the Palisades Peak quadrangle, Bonneville County, Idaho and Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-65-80, map scale 1:24,000, 1 map.

Kilburn, C., 1965, Groundwater in the upper part of the Teton Valley, Teton counties, Idaho and Wyoming: U.S. Geological Survey Water Supply Paper 1789, 60 p., 4 maps.

Walker, E.H., 1965, Ground water in the upper Star Valley, Wyoming: U.S. Geological Survey Water-Supply Paper 1809–C, 27 p., 1 pl.

1967 – Pampeyan, E.H., Schroeder, M.L., Schnell, E.M., and Cressman, E.R., 1967, Geologic map of the Driggs quadrangle, Bonneville and Teton counties, Idaho and Teton County, Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map 300, map scale 1:31,680, 1 map.

1968 – Albee, H.F., 1968, Geologic map of the Munger Mountain quadrangle, Teton and Lincoln counties, Wyoming: U.S. Geological Survey Geologic Quadrangle GQ-705, map scale 1:24,000, 1 plate.

Rohrer, W.L., 1968, Geologic map of the Fish Lake quadrangle, Fremont County, Wyoming: U.S. Geological Survey, Geologic Quadrangle Map GQ–724, 1 sheet, scale 1:24,000.

1969 – Cox, E.R., 1969, Results of water-resources investigations through 1968 in Yellowstone National Park, Wyoming: U.S. Geological Survey Open-File Report 69–60, 87 p.

Rohrer, W.L., 1969, Preliminary geologic map of the Sheridan Pass quadrangle, Fremont and Teton counties, Wyoming, U.S. Geological Survey Open-File Report OF-69-228, map scale 1:24,000, 1 map.

Schroeder, M.L., 1969, Geologic map of the Teton Pass quadrangle, Teton County, Wyoming: U.S. Geological Survey Geologic Quadrangle 793, map scale 1:24,000, 1 map.

1971 – Reed, J.C., Jr., and Love, J D., 1971, Preliminary geologic map of the Mount Bannon quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-71-233, map scale 1:24,000, 1 map.

1972 – Lindsey, D.A., 1972, Sedimentary petrology and paleocurrents of the Harebell Formation, Pinyon Conglomerate, and associated coarse clastic deposits, northwestern Wyoming: U.S. Geological Survey Professional Paper 734–B, 68 p.

Love, J.D., and Albee, H.F., 1972, Geologic map of the Jackson quadrangle, Teton County, Wyoming: U.S. Geological Survey IMAP-769-A, map scale 1:24,000, 1 map.

Love, J.D., and Keefer, W.R., 1972, Geology of sedimentary rocks in southern Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 729–D, p. D1–D60, 1 pl.

Reed, J.C., Jr., and Love, J.D., 1972, Preliminary geologic map of the Granite Basin quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-72-309, map scale 1:24,000, 1 map.

Schroeder, M.L., 1972, Geologic map of the Rendevous Peak quadrangle, Teton County, Wyoming: U.S. Geological Survey Geologic Quadrangle GQ-980, map scale 1:24,000, 1 plate.

1973 – Albee, H.F., 1973, Geologic map of the Observation Peak quadrangle, Teton and Lincoln counties, Wyoming: U.S. Geological Survey Geologic Quadrangle GQ-1081, map scale 1:24,000, 1 plate.

Cox, E.R., 1973, Water resources of Yellowstone National Park, Wyoming, Montana, and Idaho: U.S. Geological Survey Open-File Report 73–53, 161 p.

Love, J.D., 1973, Preliminary geologic map of the Two Ocean Lake quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-73-158, map scale 1:24,000, 5 leaves, 1 map.

Love, J.D., and Reed, J.C., Jr., 1973, Preliminary geologic map of the Coulter Bay quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-73-160, map scale 1:24,000, 1 map.

Reed, J. C., Jr., Love, D. W., and Love, J. D., 1973, Preliminary geologic map of the Rammel Mountain quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-73-231, map scale 1:24,000, 1 map.

Rubey, W.W., 1973a, Geologic map of the Afton quadrangle and part of the Big Piney quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-686, map scale 1:62,500, 2 sheets.

Rubey, W.W., 1973b, New Cretaceous formations in the western Wyoming Thrust Belt: U.S. Geological Survey Bulletin 1372-I, Contributions to stratigraphy, 35 p.

Schroeder, M.L., 1973, Geologic map of the Clause Peak quadrangle, Lincoln, Sublette, and Teton counties, Wyoming: U.S. Geological Survey Geologic Quadrangle GQ-1092, 1 plate.

1974 – Cox, E.R., 1974, Water resources of Grand Teton National Park, Wyoming: U.S. Geological Survey Open-File Report 74–1019, 114 p.

Love, J.D., 1974a, Geologic map of the south half of the Huckleberry Mountain quadrangle, Teton County, Wyoming: U.S. Geological Survey Open-File Report OF-74-54, map scale 1:24,000, 1 map.

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2.3 Current WWDC and USGS hydrogeologic investigations in the Snake/Salt River Basin

In addition to these existing studies, the WWDO is updating the previous Snake /Salt River Basin Water Plan (Sunrise Engineering, 2003) and constructing a hydrological model for surface flows in the basin. The U.S. Geological Survey (USGS) is currently conducting specific hydrogeologic investigations of Fish Creek near Wilson, Wyoming and the Snake River Alluvial aquifer in the vicinity of the Jackson Hole Airport. Reports of these investigations can be obtained from the USGS publications website: http://pubs.er.usgs.gov/. Additionally, the USGS continues to collect real time streamflow data and periodic water quality at 16 USGS gaging stations located in the basin: http://waterdata.usgs.gov/wy/nwis/current/?type=flow.

2.4 Current Available Groundwater Determination

The previous investigations, noted above, examined the hydrogeology of geographic areas of varying scale that fall partly or entirely within the Snake/Salt River Basin. The study area of this and the previous memorandum (Sunrise Engineering, 2003) include the surface drainages of the Snake/Salt River that lie within the borders of the state of Wyoming as well as watersheds in Idaho that are tributary to the Wyoming Snake Salt River Basin (**fig. 3-1**).

A detailed hydrostratigraphy of the Snake Salt River Basin was developed by the USGS for this study 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 (**pls. 4-6**), and on **plate 2**.

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

- Effects of structure on groundwater distribution and flow (**section 5.4** and **chapter 7**),
- Potential hydrothermal resources (**chapter 4**),
- Aquifer vulnerability and potential sources of groundwater contamination (**section 5.6**),
- Comparisons of calculated aquifer(s)-specific recharge volumes with updated precipitation data, and current and projected beneficial uses (**section 6.2**),
- A basinwide water balance (**chapter 8**),
- A detailed listing and summary of historic groundwater development studies by the WWDC in the Snake Salt 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 Snake/Salt 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 correlations between multiple, disparate datasets. 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 cites data sources for each map and figure presented.

Additionally, metadata (qualifying information on the GIS datasets) is commonly 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 to obtain additional information. The metadata associated with the Snake/Salt River Basin maps are provided online 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 readability considerations.

Chapter 3

Description of the study area

Karl Taboga, James Stafford, and Paul Taucher

This study examines groundwater resources that underlie the Snake/Salt River drainage basin in Wyoming, as well as tributary areas in Idaho (**fig. 3-1**). The Snake/Salt River Basin in Wyoming covers approximately 5,113 square miles (3.27 million acres), or 5.2 percent of Wyoming's surface area. The tributary watershed in southeastern Idaho is small, about 432 square miles (0.28 million acres). In Wyoming, the Snake/Salt River Basin includes 81 percent of Teton, 28 percent of Lincoln, 8.5 percent of Sublette, and 1.7 percent of Fremont counties. In Idaho, the tributary watershed covers 4.5 percent of Bonneville, 18.3 percent of Caribou, 0.9 percent of Fremont, and 0.12 percent of Teton Counties. Unless specific references are made to the Idaho tributary areas, references to the Snake/Salt River Basin in this memorandum include only the Wyoming portion of the watershed.

Although, the Snake/Salt River Basin encompasses about 5.2 percent of Wyoming's total surface area, it serves as home to approximately 34,500 people or about 6.0 percent of the state's current population (WDAIEAD, 2014). The Snake/Salt River Basin contains five incorporated municipalities (Jackson, Afton, Star Valley Ranch, Alpine, and Thayne), 21 U.S. Census Designated Places (CDP), and a substantial rural population. The index map in **figure 3-1** shows townships, major roads, and incorporated municipalities within the Snake/Salt River Basin.

3.1 Physiography, landforms, topography, and surface drainage

The Snake/Salt River drainage basin is located entirely within the Middle Rocky Mountain Physiographic Province (WSGS, 2014). Major drainages, reservoirs, and physiographic features of the Snake/Salt River Basin are shown on **figure 3-2**. A map of the physiographic provinces of Wyoming is available online at http://www.wsgs.uwyo.edu/Research/Geology/images/Final/Elevations.pdf.

The overall physiography of the Snake/Salt River Basin consists of a deeply eroded geologic foundation superimposed on the Overthrust Belt in the south, the Absaroka and Yellowstone Plateau volcanic systems to the north, Laramide and subsequent uplift structures to the north and east and Basin and Range Province structures to the west. The Overthrust Belt, of eastern Idaho, northern Utah, and western Wyoming is composed of strike ridges and valleys formed during the Sevier Orogeny (125 – 55 million years ago). During that period, rocks of Paleozoic and Mesozoic age were thrust eastward by low angle, imbricated (overlapping), westward dipping thrust faults that form five thrust systems along with their associated thrust sheets. The extent of the Snake/Salt River drainage basin examined in this study (**fig. 3-1**) encompasses portions of the four earliest Sevier thrust systems. The Wyoming portion of the Snake/Salt River Basin includes the three most eastern thrust systems: the Crawford, Absaroka, and Darby sheets.

The Laramide structures (Hoback and Jackson basins and the Gros Ventre Range) on the eastern periphery of the Snake/Salt River Basin are composed of large anticlinal uplifts that have crystalline basement 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, and glacial and fluvial processes.

The volcanic rocks of the Absaroka Range were formed during an period of volcanism that occurred from 53 to 35 million years ago. Subsequent deformation of the Absaroka volcanic suite occurred as a result of late and post-Laramide Laramide folding and faulting, intrusive igneous activity, slope processes, and post-volcanic extension and compaction. In comparison, the large, Pleistocene, mafic volcanic field that composes the Yellowstone-Snake River Plain (YSRP) was formed from 16 to 1 million-years ago. The YSRP volcanic system, which extends into parts of Nevada, Idaho, Montana, and Wyoming, is one of the Earth's largest silica-rich volcanic systems on Earth.

Following the Sevier and Laramide orogenies, a period of geologic extension started in the late Eocene, about 35 - 40 million years ago, and

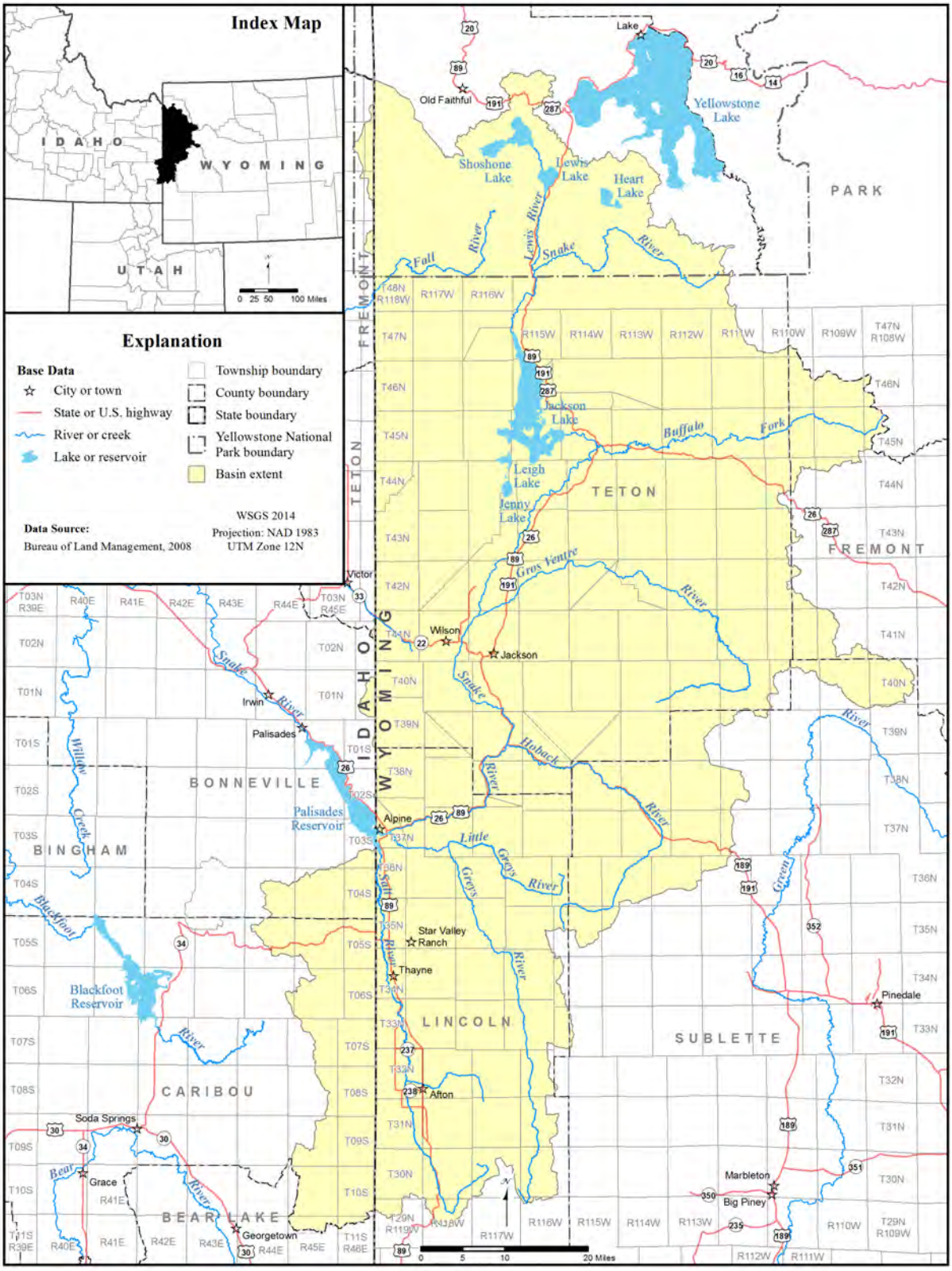


Figure 3-1. Municipality, road, township, and range index map, Snake/Salt River Basin.

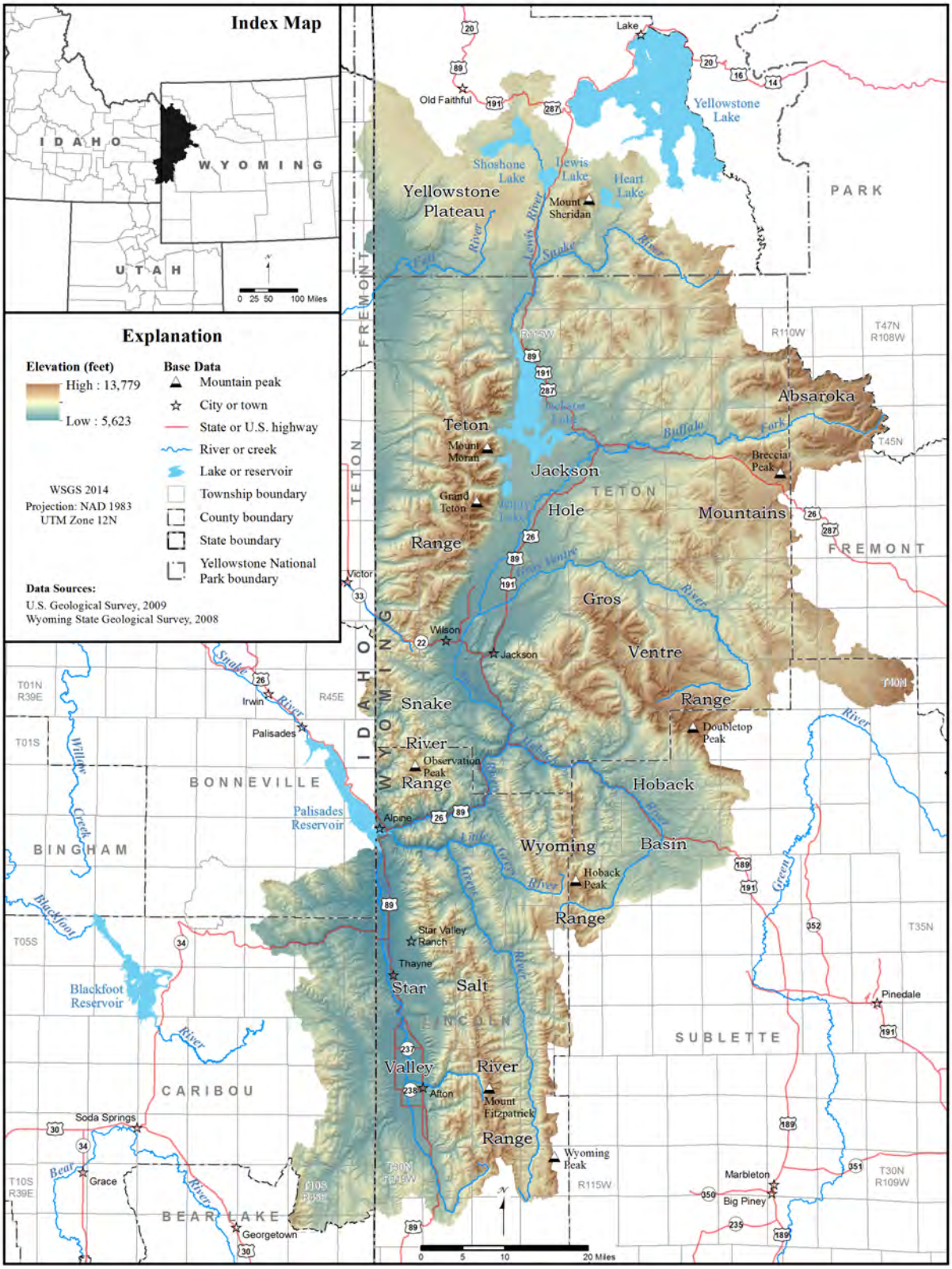


Figure 3-2. Physiographic features, drainages, and bodies of water, Snake/Salt River Basin.

continues into the present. The extension caused the formation of numerous normal faults that form the foundation of the Snake/Salt River drainage. During the Sevier Orogeny and the more recent period of geological extension, erosion, mass wasting, and fluvial processes wore down the highlands and deposited sediments in the valleys. These processes, combined with concurrent and continued faulting, resulted in the present physiography characterized by valleys alternating with north-south trending mountain ranges of variable areal scale and elevation. Elevations in the Snake Salt River Basin in Wyoming range from 5,623 feet above mean sea level where the Snake/Salt River enters the headwaters of Palisades Reservoir to 13,775 feet at the summit of Grand Teton. Detailed discussions of the geography of the Snake Salt River Basin are provided in **chapter 4** of this study.

Surface drainage in the Snake/Salt River Basin is controlled by topography. Perennial streams receive a large percentage of their source waters from overland flow associated with snowmelt and rainfall that originates in semi-humid and humid, mountainous, headwater regions and from persistent baseflow (Sunrise Engineering, 2003). Most ephemeral flow occurs in response to springtime snowmelt and to intense, short duration, rainfall events characteristic of transient, convective thunderstorms. Streamflows are also affected by vegetation, temperature, artificial diversions, and complex interconnections with groundwater.

Major drainages, reservoirs, and physiographic features of the Snake/Salt River Basin are shown on **figure 3-2** and **plate 1**. The basin encompasses the Snake/Salt River system and its tributary drainages. The Snake River is the major tributary to the Columbia River. The mainstem of the Snake River begins at the confluence of three small headstreams on the southwestern flank of Two Oceans Plateau in Yellowstone National Park. Primary tributaries that confluence with the Snake River in Wyoming include Buffalo Fork, Gros Ventre, Hoback, and Greys rivers. The headwaters of the Salt River flow from the slopes below Mount Wagner in the southern Salt Creek Range located in central Lincoln County. The Salt River confluences with the Snake River in Palisades Reservoir near Alpine, Wyoming.

3.2 Climate, precipitation, and vegetation

Climate within the Snake/Salt River Basin is primarily a function of elevation and to a lesser degree, latitude and topography. Climate types range from semi-arid continental within the interior basins, to humid-alpine in the bordering mountain ranges. The mountain ranges capture much of the atmospheric moisture through orographic uplift, resulting 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. Annual precipitation increases with surface elevation (**fig. 3.3**) and can exceed 95 inches a year in the high mountain headwater areas of the Tetons. Annual precipitation averages 33 inches over the entire basin (PRISM, 2013). Most precipitation within the basin occurs as snowfall during the winter and early spring and as convective thunderstorms during late spring and summer months (Ahern and others, 1981).

The diversity and distribution of vegetation within the Snake/Salt River Basin is primarily influenced by elevation. The abundance of grasses, shrubs, a variety of woodland trees (primarily conifers), and other species generally increases with elevation (hence, precipitation) up to timberline above which, alpine tundra species of lichens, low shrubs, and grasses dominate flora. The dominant ecological zones are, generally, sagebrush steppe/shrubland (mixed prairie grasses and shrubs; primarily sagebrush) on the plains, mixed deciduous and coniferous forest along drainages, sub-alpine spruce-fir forest on mountain flanks and at the highest elevations, alpine tundra.

3.3 Population distribution, land use, and land ownership

The Wyoming Department of Administration and Information Economic Analysis Division

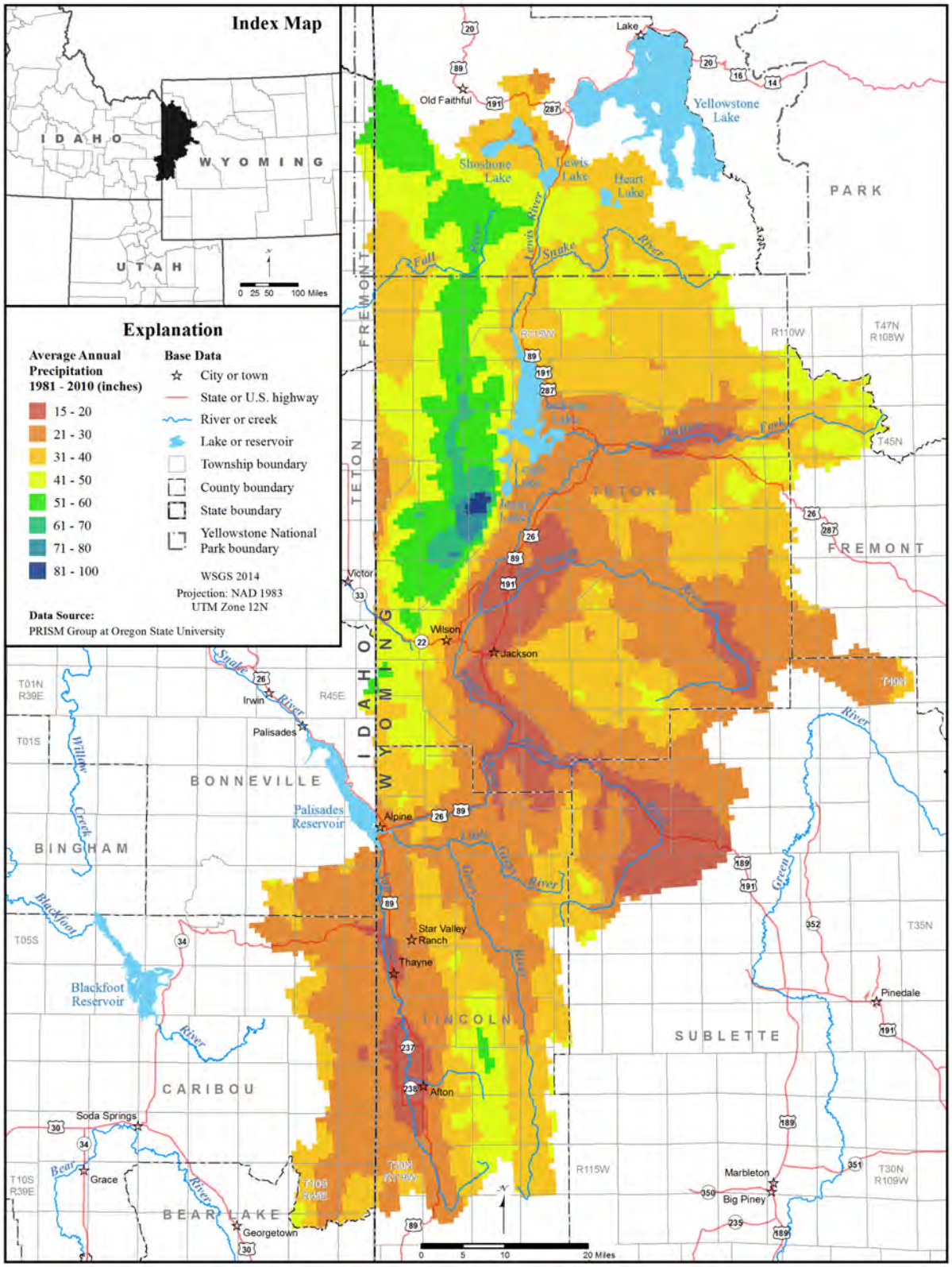


Figure 3-3. Average annual precipitation (1981 - 2010), Snake/Salt River Basin.

(WDAIEAD) estimates that 34,500 people or about 6.0 percent of the state's current population (WDAIEAD, 2014) reside in the Wyoming portion of the Snake/Salt River basin. The basin contains five municipalities and 21 U.S. Census Designated Places (U.S. Census Bureau, 2010) in Wyoming; most of these communities are located along or within a few miles of the rivers. Additional demographic information for the basin can be found online: http://waterplan.state.wy.us/plan/snake/snake-plan.html.

Land use in the Snake/Salt River Basin is controlled primarily by elevation, climate, precipitation, and land ownership. Above timberline, the alpine areas are generally used for recreational purposes. At lower elevations, thickly forested areas are utilized for recreation and limited logging. Grazing is the dominant use for rangelands, foothills, and riparian areas. Agriculture plays a significant role in the basin; approximately 3 percent (99,071 acres) of the basin's surface area consists of irrigated cropland (Sunrise Engineering, 2003). Crop producing areas are located mainly along the Salt River and sparsely scattered along the Snake River mainstem and the Hoback and Gros Ventre rivers (Sunrise Engineering, 2003). A map illustrating the distribution of the broad categories of land cover in the northwestern U.S., with downloadable GIS land cover data, is provided online by the USGS at: http://gapanalysis.usgs.gov/gaplandcover/data/.

Approximately 90 percent of the land area of the Snake/Salt River Basin is federally owned. In general, federal land in the basin is managed by the U.S. Forest Service (~2.26 million acres), the National Park Service (655,521 acres), and the Bureau of Land Management (8,056 acres). Privately owned lands, concentrated along rivers and streams, constitute about 7.8 percent of the land in the basin; 0.4 percent is owned by the state of Wyoming; and less than 2 percent is owned or managed by other entities. A map of state, federal, and private land ownership in Wyoming is available online via the Wyoming Water Development Office's 2007 Statewide Water Plan Online Presentation Tool: http://waterplan.wrds.uwyo.edu/fwp/figures/pdf/Fig3-2_3-3.pdf.

Chapter 4

Geologic Setting

Martin C. Larsen

The Snake/Salt River Basin comprises approximately 5,500 square miles (16.80 million acres) in western Wyoming and extends into southeastern Idaho. In Wyoming, the Snake/Salt River Basin encompasses nearly all of Teton County and portions of Lincoln, Sublette, and Fremont counties. The basin is bounded by the Overthrust Belt to the west and south, the Green River Basin to the southeast, the Wind River Range to the east-southeast, the Bighorn Basin to the east, and the Yellowstone River Drainage to the north. Of all Wyoming basins, the Snake/Salt River Basin has the most complex geology. The geologic settings for this drainage encompass:

- The Overthrust Belt, which includes three major mountain chains (Salt River, Wyoming, and Snake River Ranges) related to the Sevier Orogeny;
- Two structural basins (Jackson Hole and Hoback) and three mountain ranges (Gros Ventre, Teton, and Absaroka) associated with the Laramide Orogeny;
- Range-front normal faulting and two structural basins associated with the Basin and Range Province; and
- The Yellowstone Plateau, and the Absaroka Volcanic province.

An extensive set of figures, maps and plates are included in this report to depict the basin's complex geologic settings. **Plate 1** illustrates the bedrock geology of the Snake/Salt River Basin in Wyoming and a small portion of southeastern Idaho overlain on a base map that shows highway, township, state and county data. Inset maps present the elevations of the Precambrian basement and lineaments. **Appendix A** contains detailed descriptions of the geologic units shown in **plate 1**. Six cross-sections, **figures 4-1** through **4-6**, show typical subsurface structure in the Snake/Salt River Basin. Isopach maps of the major aquifers in the Snake/Salt River Basin are unavailable.

4.1 General geologic history

The correlation between the major structural and lithologic elements significantly influences the availability of groundwater within the Snake/Salt River Basin. The geologic history relevant to Snake/Salt River Basin groundwater resources begins with the nonconformable deposition of transgressive marine sediments onto underlying Precambrian basement rocks. From that time forward, a general geologic history that describes the development of the stratigraphic, structural, and volcanic elements the Snake/Salt River Basin is as follows:

1. Paleozoic strata in the Snake/Salt River Basin were deposited in numerous marine and nonmarine environments related to periodic transgressive and regressive environments. Sandstone, shale, conglomerate, and limestone are the dominant lithologies, with less extensive dolomite. Deposition in the Paleozoic Era was broken by long periods of erosion, as indicated by several regional unconformities in the geologic record.

2. The Mesozic Era was a time of shallow seas with deposition of interbedded layers (in decreasing abundance) of sandstone, siltstone, shale, carbonates, and evaporites. An emergent transition to terrestrial environments during the Late Triassic and Early Jurassic epochs deposited marginal marine, eolian, fluvial, and paludal sandstone and shale.

3. Sevier and Laramide deformation affected the Southwest Cordillera between earliest Cretaceous and Early Eocene time (approximately 140 - 35 million years ago). The Sevier Orogeny is defined by "thin-skinned" deformation, characterized by shallow thrusts faults. Parallel north-south trending Sevier-aged faults in the Overthrust Belt are generally younger to the east. Laramide deformation was a period of intense folding and faulting with large-scale reverse and thrust faults and asymmetric folds. The "thick-skinned" deformation of the Laramide Orogeny included Precambrian basement-cored mountain ranges and uplifts that surrounded and partitioned the Snake/Salt River Basin structural basins. During

the Middle Eocene, massive eruptions related to the Absaroka Volcanic Province emplaced rhyolitic and basaltic volcanic material along the northern side of the Snake/Salt River Basin.

4. Late Tertiary Basin and Range normal faulting, coupled with volcanic activity from the Yellowstone hotspot, has overprinted many of the Sevier and Laramide geologic relationships. Uplift during the past five million years resulted in erosion of Tertiary strata, stripping the Laramide and Sevier structures, and shaping the present day landscape of the Snake/Salt River Basin. Tertiary-age rocks include volcanic deposits and an assortment of sedimentary units, including conglomerates, sandstone, limestone, and mudstone. Some of the Tertiary volcanics include andesitic flows, breccias, and porphyries that resemble breccias of the Yellowstone and the Absaroka volcanic regions.

5. The youngest units in the Snake/Salt River Basin are unconsolidated Quaternary alluvial, colluvial, lacustrine, and glacial deposits of varying thicknesses. These deposits, some several hundreds of feet thick, consist of interbedded mixtures of clay, silt, sand and gravel, landslide deposits, glacial deposits, and lacustrine sediments. Quaternary glacial deposits correlate to the advance and retreat of the Bear Lake and Pinedale glaciations (15,000 years before present).

4.2 Structural geology

The Snake/Salt River Basin encompasses three characteristic structural provinces: 1) the continental shelf deposits, which includes the Teton and Gros Ventre ranges; 2) west of the shelf zone, structurally deformed passive margin Paleozoic and Mesozoic units that include the Wyoming, Salt and Snake River ranges (i.e., the Overthrust Belt); and 3) the volcanism of the Yellowstone Plateau and Absaroka Province. The dominant structural features that form the backbone of the Teton and Gros Ventre ranges consist of basement core, broad, asymmetrical anticlines, northeast dipping thrust faults, and parallel folds. The initial stages of forming Teton and Gros Ventre structures were concurrent with the early phases of the Laramide deformation. These major structures controlled the character and trend of the later, Snake, and Salt River structures in Wyoming. The structural architecture of the Salt River, and Snake River Ranges are also the result of the Sevier "thin-skinned" deformation. The Overthrust Belt located in southwestern Wyoming and neighboring areas of Idaho and Utah, is a north-south trending, elongate fold and thrust belt that encompasses structurally deformed Paleozoic and Mesozoic units. The complex structural deformation in this region includes folding, imbricated thrust faults, and reverses faulting. During the Sevier Orogeny, thrust sheets were pushed eastward, resulting in the parallel thrust faults with the younger thrust belts to the east.

Beginning in the Tertiary and continuing to the present day, some Laramide and Sevier structural features have been overprinted or transected by north-south tending, high-angle normal faults due to Neogene Basin and Range extension. Normal faults are coincident with north-northwest tending folds and thrust fault bounded uplifts that define a complex set of half-grabens. Holocene-age displacement is apparent on some of the normal faults.

The topography of the Snake/Salt River Basin is reflected by major structural features that uplifted, folded, faulted, and eroded Precambrian basement and the Phanerozoic sedimentary and volcanic deposits. The insert map in **plate 1** is a structural contour map of the Precambrian basement surface in the Snake/Salt River Basin that shows a general northwest-southeast lineament trend. The geologic cross-sections on **figures 4-2** through **4-7** show Precambrian basement rocks overlain by varying thicknesses of Phanerozoic formations, all deformed by large-scale folding and faulting.

The major structural elements of the Snake/Salt River Basin (**fig. 4-1**) comprise:

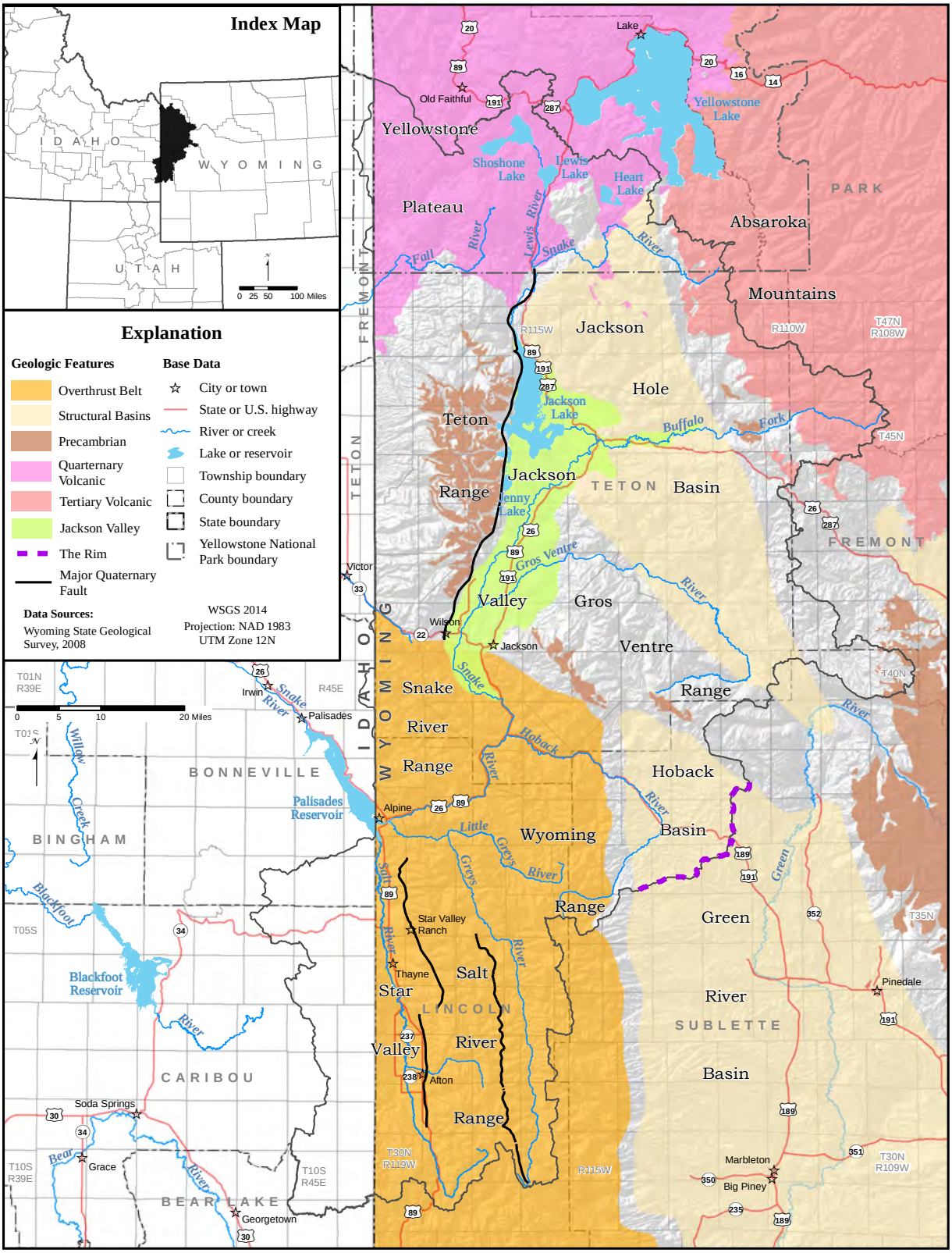
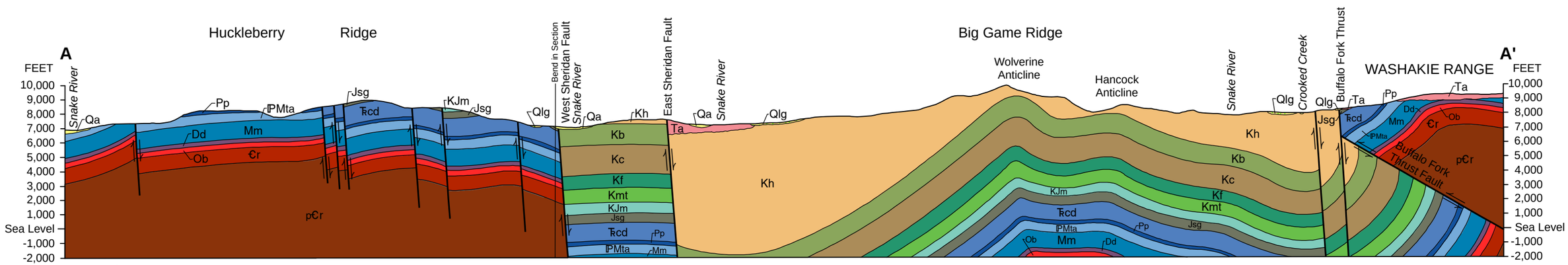


Figure 4-1. Geologic features, Snake/Salt River Basin.

Cross Section A - A'



No Vertical Exaggeration

Index Map and Line of Section

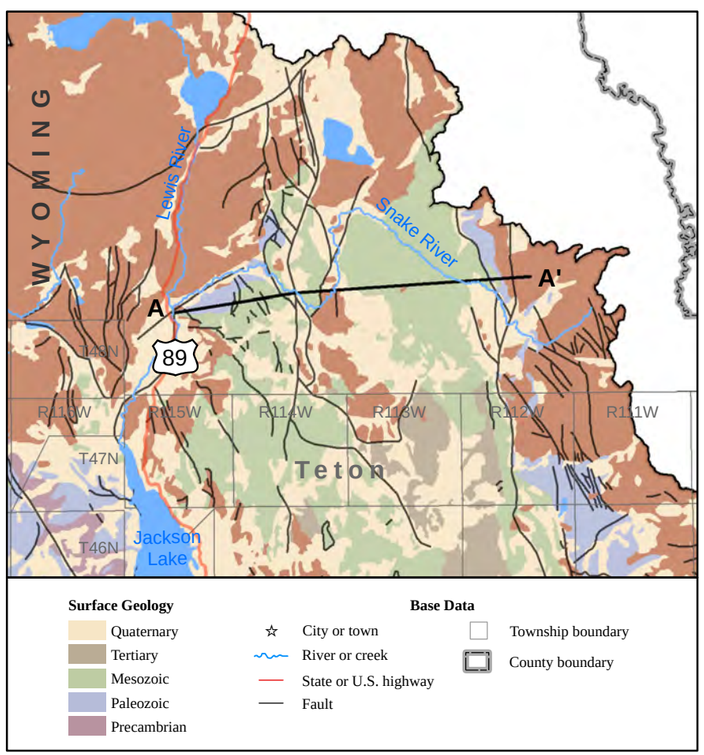


Figure 4-2. Geologic cross section A-A'.

Geologic Units

CENOZOIC

Quaternary

- Qa — Alluvium and terrace deposits
- Qlg — Landslide and glacial deposits

Tertiary

- Ta — Absaroka Volcanic Supergroup

MESOZOIC

Cretaceous

- Kh — Harebell Formation
- Kb — Bacon Ridge Sandstone
- Kc — Cody Shale
- Kf — Frontier Formation
- Kmt — Mowry and Thermopolis Shales

MESOZOIC (cont.)

Cretaceous-Jurassic

- KJm — Cloverly and Morrison Formations

Jurassic

- Jsg — Sundance and Gypsum Spring Formations

Triassic

- Ŧcd — Chugwater and Dinwoody Formations

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Pennsylvanian-Mississippian

- IPMta — Tensleep Sandstone and Amsden Formation

PALEOZOIC (cont.)

Mississippian

- Mm — Madison Limestone

Devonian

- Dd — Darby Formation

Ordovician

- Ob — Bighorn Dolomite

Cambrian

- Ꞓr — Cambrian rocks

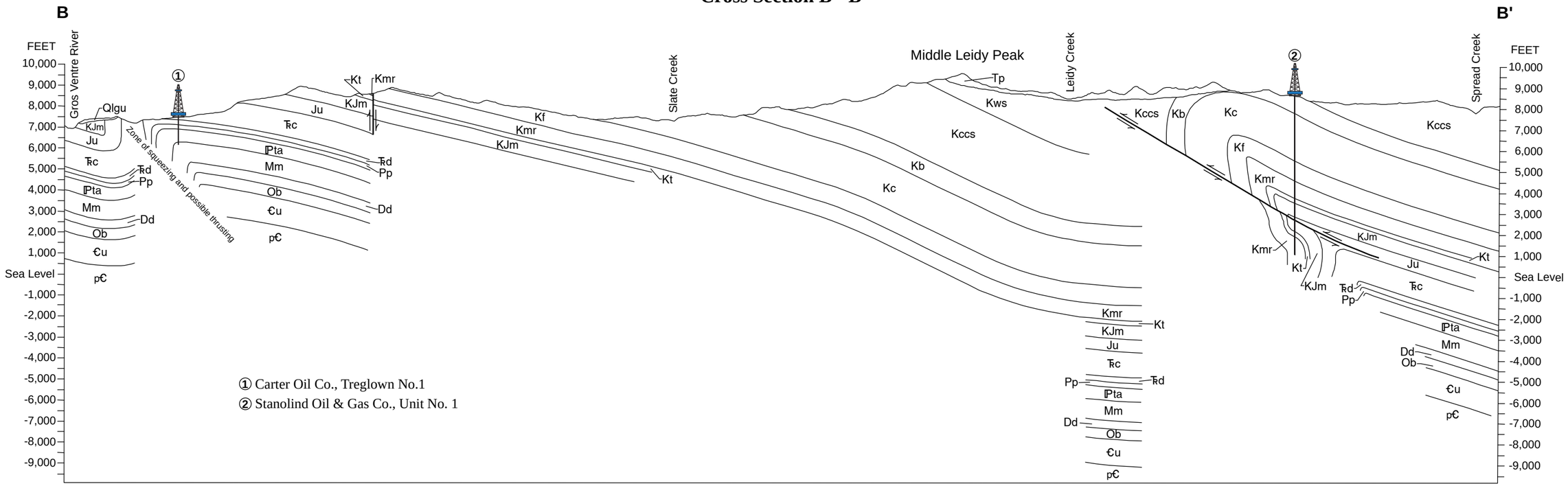
PRECAMBRIAN

- pꞒr — Precambrian rocks

Fault

Love, J.D., and Keefer, W.R., 1975, Geology of sedimentary rocks in southern Yellowstone National Park, Wyoming: U.S. Geological Survey, Professional Paper 729-D, scale 1:62,500.

Cross Section B - B'



No Vertical Exaggeration

Index Map and Line of Section

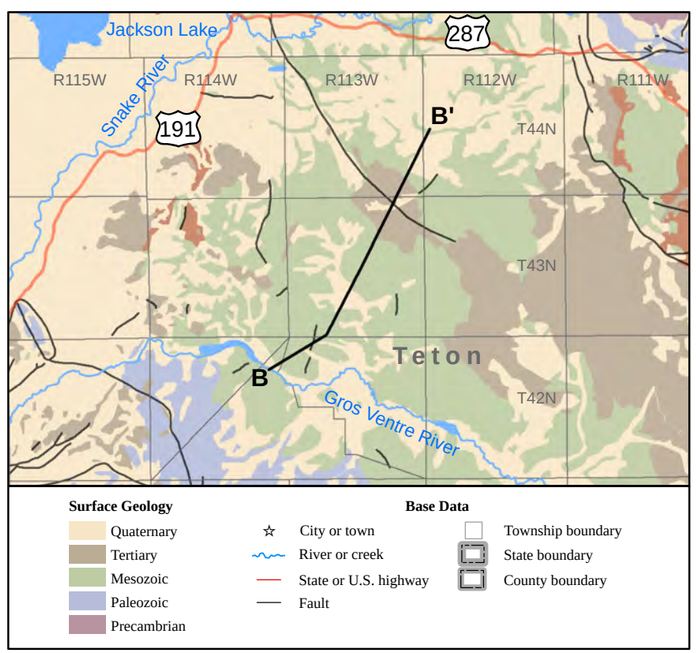


Figure 4-3. Geologic cross section B-B'.

Geologic Units

CENOZOIC

Quaternary

Qal – Alluvium

Qlsd – Landslide debris

Qlgu – Landslide and glacial debris

Tertiary

Tp – Pinyon Conglomerate and greenish-gray and brown sandstone and shale sequence undivided

MESOZOIC

Cretaceous

Kws – White sandstone sequence

Kccs – Lenticular sandstone and shale sequence and coaly sequence, undivided

Kb – Bacon Ridge Sandstone

Kc – Cody Shale

MESOZOIC (cont.)

Cretaceous (cont.)

Kf – Frontier Formation

Kmr – Mowry Shale

Kt – Thermopolis shale and Muddy sandstone

Cretaceous-Jurassic

KJm – Cloverly and Morrison Formations

Jurassic

Ju –Jurassic rocks undivided

Triassic

Ꞧc – Chugwater Formation

Ꞧd – Dinwoody Formation

PALEOZOIC

Permian

Pp – Phosphoria Formation

PALEOZOIC (cont.)

Pennsylvanian-Mississippian

IPta – Tensleep and Amsden Formations

Mississippian

Mm – Madison Limestone

Devonian

Dd – Darby Formation

Ordovician

Ob – Bighorn Dolomite

Cambrian

Ꞓu – Cambrian rocks undivided

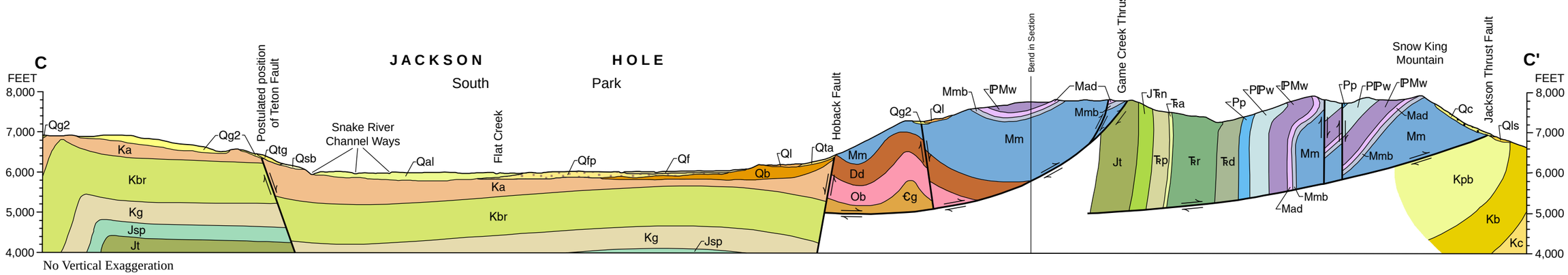
PRECAMBRIAN

p€ – Precambrian igneous and metamorphic rocks

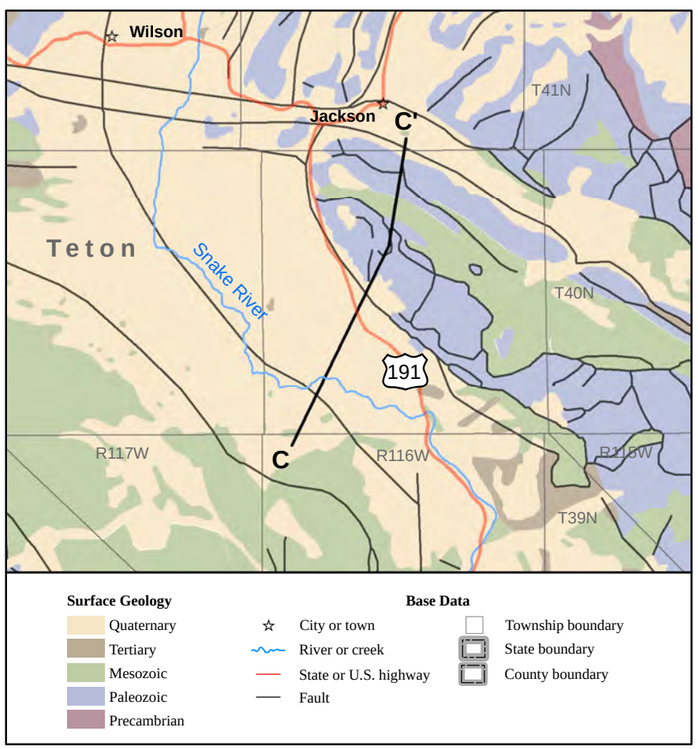
Fault

Love, J.D., Keefer, W.R., Duncan, D.C., Bergquist, H.R., and Hose, R.K., 1951, Geologic map of the Spread Creek-Gros Ventre River area, Teton County, Wyoming: U.S. Geological Survey, Oil and Gas Investigations Map OM-118, scale 1:48,000.

Cross Section C - C'



Index Map and Line of Section



Geologic Units

CENOZOIC

Quaternary

- Qal — Alluvium
- Qfp — Floodplain deposits
- Qtg — Terrace deposits undifferentiated
- Qc — Colluvium
- Qls — Landslide debris
- Qta — Talus
- Qf — Alluvial fan deposits
- Qsb — Slump block
- Ql — Loess
- Qg2 — Glacial deposits and related outwash gravels
- Qb — Lithified talus breccia

MESOZOIC

Cretaceous

- Kpb — Post-Bacon Ridge rocks
- Kb — Bacon Ridge Sandstone
- Kc — Cody Shale

MESOZOIC (cont.)

Cretaceous (cont.)

- Ka — Aspen Shale
- Kbr — Bear River Formation
- Kg — Gannett Group

Jurassic

- Jsp — Stump and Preuss Sandstones
- Jt — Twin Creek Limestone

Jurassic-Triassic

- JŦn — Nugget Sandstone

Triassic

- Ŧp — Popo Agie Member (Chugwater Formation)
- Ŧa — Alcova Limestone Member (Chugwater Formation)
- Ŧr — Red Peak Member (Chugwater Formation)
- Ŧd — Dinwoody Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation

PALEOZOIC (cont.)

Permian-Pennsylvanian

- PIPw — Wells Formation upper unit

Pennsylvanian-Mississippian

- IPMw — Wells Formation lower unit

Mississippian

- Mad — Darwin Sandstone Member (Amsden Formation)
- Mmb — Bull Ridge Member (Madison Limestone)
- Mm — Main body Madison Limestone

Devonian

- Dd — Darby Formation

Ordovician

- Ob — Bighorn Dolomite

Cambrian

- Ꞓg — Gallatin Limestone

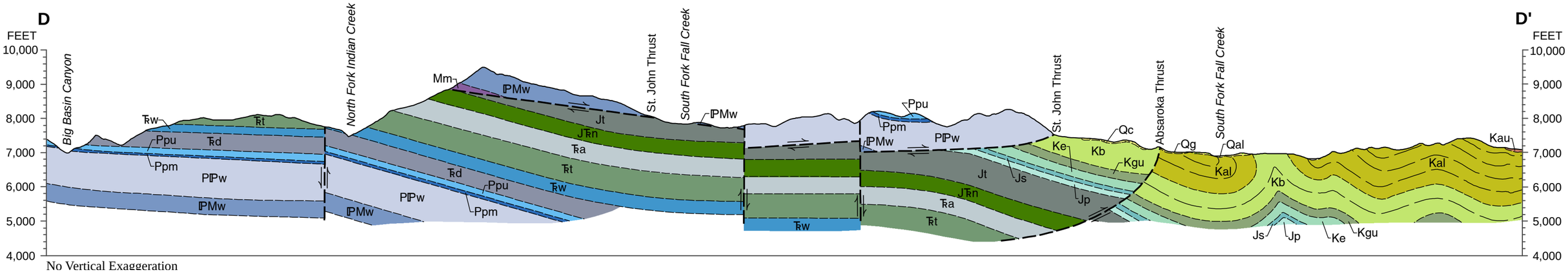
Fault

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

Love, J.D., and Albee, H.F., 1972, Geologic map of the Jackson quadrangle, Teton County, Wyoming: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-769-A, scale 1:24,000.

4-41

Cross Section D - D'



Index Map and Line of Section

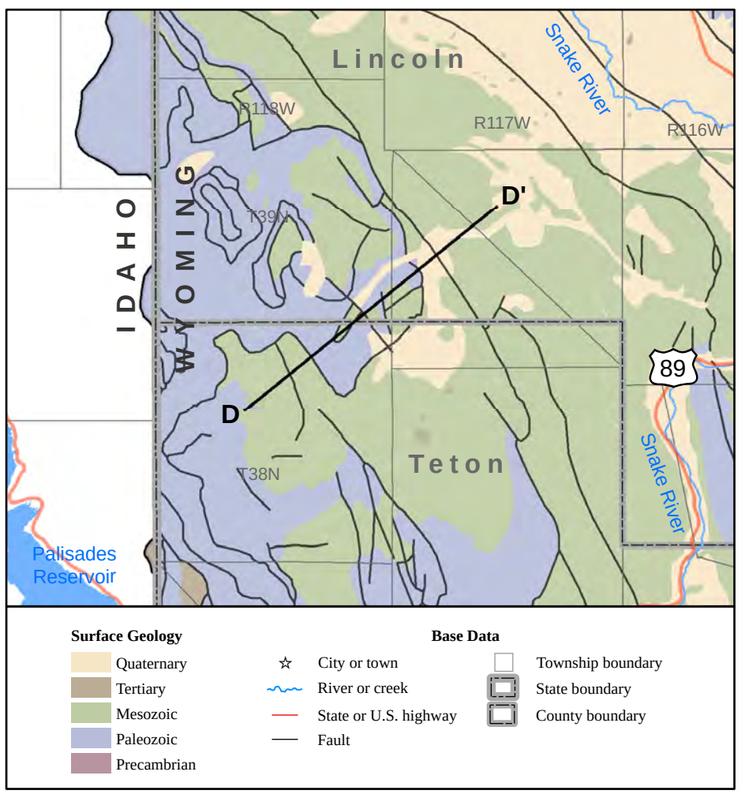


Figure 4-5. Geologic cross section D-D'.

Geologic Units

CENOZOIC

Quaternary

- Qal — Alluvium
- Qc — Colluvium
- Qg — Glacial deposits

MESOZOIC

Cretaceous

- Kau — Upper Aspen Formation
- Kal — Lower Aspen Formation
- Kb — Bear River Formation
- Kgu — Gannett Group
- Ke — Ephraim Conglomerate

MESOZOIC (cont.)

Jurassic

- Js — Stump Sandstone
- Jp — Preuss Formation
- Jt — Twin Creek Limestone

Jurassic-Triassic

- JŦn — Nugget Sandstone

Triassic

- Ŧa — Ankareh Formation
- Ŧt — Thaynes Formation
- Ŧw — Woodside Formation
- Ŧd — Dinwoody Formation

PALEOZOIC

Permian

- Ppu — Phosphoria Formation
- Ppm — Mead Peak Member (Phosphoria Formation)

Permian-Pennsylvanian

- PIPw — Upper Wells Formation

Pennsylvanian-Mississippian

- IPMw — Lower Wells Formation

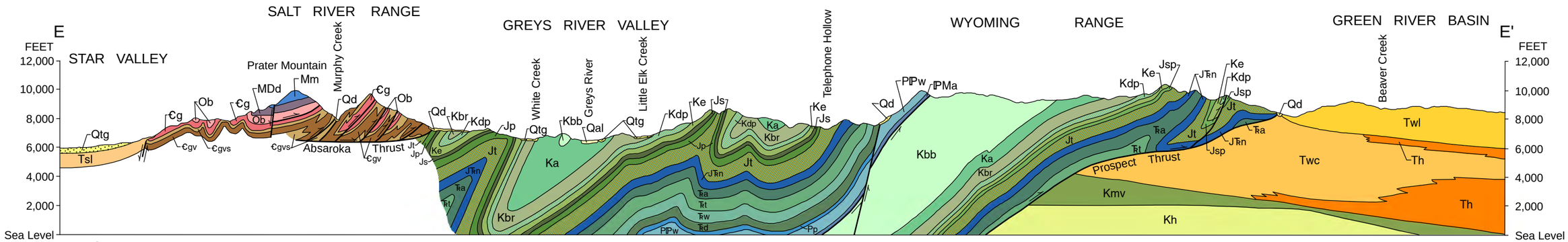
Mississippian

- Mm — Mission Canyon Limestone

Fault

Love, J.D., and Keefer, W.R., 1975, Geology of sedimentary rocks in southern Yellowstone National Park, Wyoming: U.S. Geological Survey, Professional Paper 729-D, scale 1:62,500.

Cross Section E - E'



Vertical Exaggeration 1.5x

Love, J.D., and Keefer, W.R., 1975, Geology of sedimentary rocks in southern Yellowstone National Park, Wyoming: U.S. Geological Survey, Professional Paper 729-D, scale 1:62,500.

Index Map and Line of Section

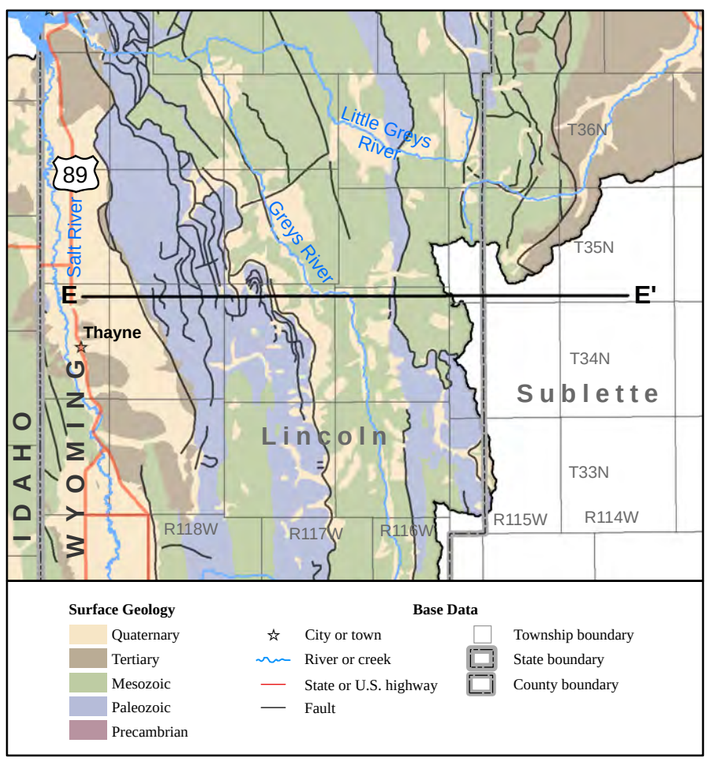


Figure 4-6. Geologic cross section E-E'.

Geologic Units

CENOZOIC

Quaternary

- Qal — Floodplain and alluvial fan deposits
- Qd — Rock debris and colluvium
- Qtg — Terrace gravels and older alluvium

Tertiary

- Tsl — Salt Lake Formation
- Twl — La Barge Member (Wasatch Formation)
- Twc — Chappo Member (Wasatch Formation)
- Th — Hoback Formation

MESOZOIC

Cretaceous

- Kbb — Blind Bull Formation
- Kmv — Mesaverde Sandstone
- Kh — Hillard Shale
- Ka — Aspen Formation
- Kbr — Bear River Formation

MESOZOIC (cont.)

Cretaceous (cont.)

- Kdp — Gannett Group from top to base of Peterson
- Ke — Ephraim Conglomerate

Jurassic

- Js — Stump Sandstone
- Jp — Preuss Redbeds
- Jsp — Stump Sandstone and Preuss Redbeds
- Jt — Twin Creek Limestone

Jurassic-Triassic

- JTRn — Nugget Sandstone

Triassic

- TRa — Ankareh Redbeds
- TRt — Thaynes Limestone
- TRw — Woodside Redbeds
- TRd — Dinwoody Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian-Pennsylvanian

- PIPw — Wells Formation

Pennsylvanian-Mississippian

- IPMa — Amsden Formation

Mississippian

- Mm — Madison Limestone

Mississippian-Devonian

- MDd — Darby Formation

Ordovician

- Ob — Bighorn Dolomite

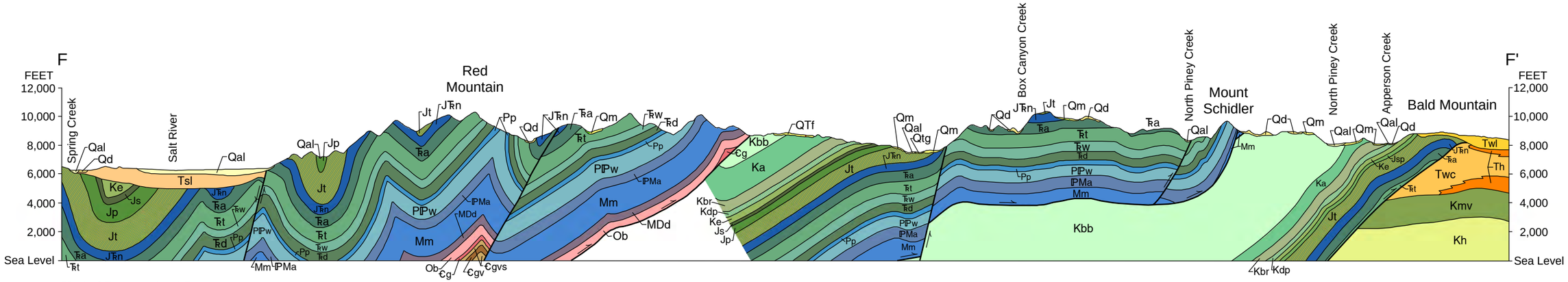
Cambrian

- Ꞓg — Gallatin Limestone
- Ꞓgvs — Gros Ventre Shale
- Ꞓgv — Gros Ventre Formation middle limestone member

Fault

4-43

Cross Section F - F'



Vertical Exaggeration 1.5x

Love, J.D., and Keefer, W.R., 1975, Geology of sedimentary rocks in southern Yellowstone National Park, Wyoming: U.S. Geological Survey, Professional Paper 729-D, scale 1:62,500.

Index Map and Line of Section

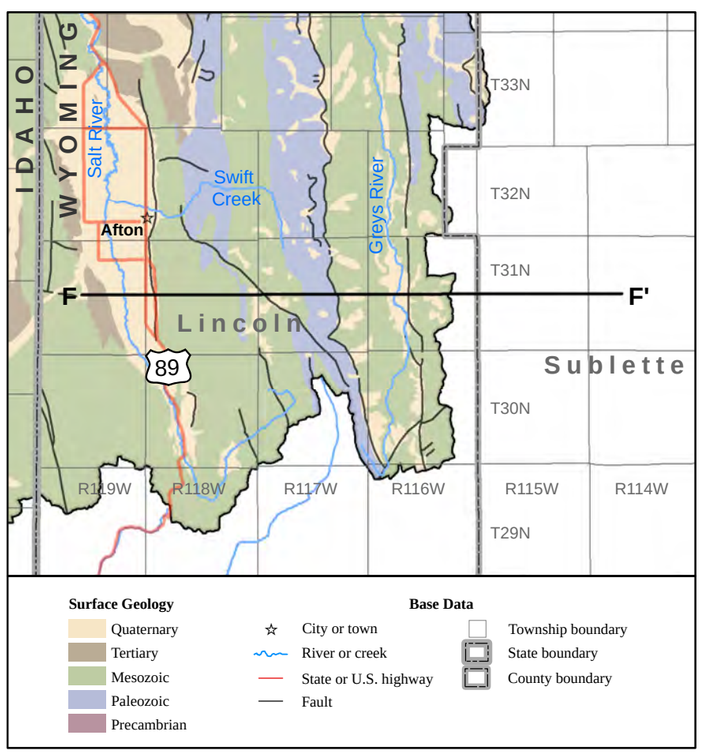


Figure 4-7. Geologic cross section F-F'.

Geologic Units

CENOZOIC

Quaternary

- Qal — Floodplain and alluvial fan deposits
- Qd — Rock debris and colluvium
- Qtg — Terrace gravels and older alluvium
- Qm — Glacial till and moraine

QUATERNARY-CENOZOIC

Quaternary-Tertiary

- QTf — Fanglomerate or till

CENOZOIC

Tertiary

- Tsl — Salt Lake Formation
- Twl — La Barge Member (Wasatch Formation)
- Twc — Chappo Member (Wasatch Formation)
- Th — Hoback Formation

MESOZOIC

Cretaceous

- Kbb — Blind Bull Formation
- Kmv — Mesaverde Sandstone

MESOZOIC (cont.)

Cretaceous (cont.)

- Kh — Hillard Shale
- Ka — Aspen Formation
- Kbr — Bear River Formation
- Kdp — Gannett Group from top to base of Peterson
- Ke — Ephraim Conglomerate

Jurassic

- Js — Stump Sandstone
- Jp — Preuss Redbeds
- Jsp — Stump Sandstone and Preuss Redbeds
- Jt — Twin Creek Limestone

Jurassic-Triassic

- JTRn — Nugget Sandstone

Triassic

- TRa — Ankareh Redbeds
- TRt — Thaynes Limestone
- TRw — Woodside Redbeds
- TRd — Dinwoody Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian-Pennsylvanian

- PIPw — Wells Formation

Pennsylvanian-Mississippian

- IPMa — Amsden Formation

Mississippian

- Mm — Madison Limestone

Mississippian-Devonian

- MDd — Darby Formation

Ordovician

- Ob — Bighorn Dolomite

Cambrian

- Ꞓg — Gallatin Limestone
- Ꞓgvs — Gros Ventre Shale
- Ꞓgv — Gros Ventre middle limestone member

Fault

4-44

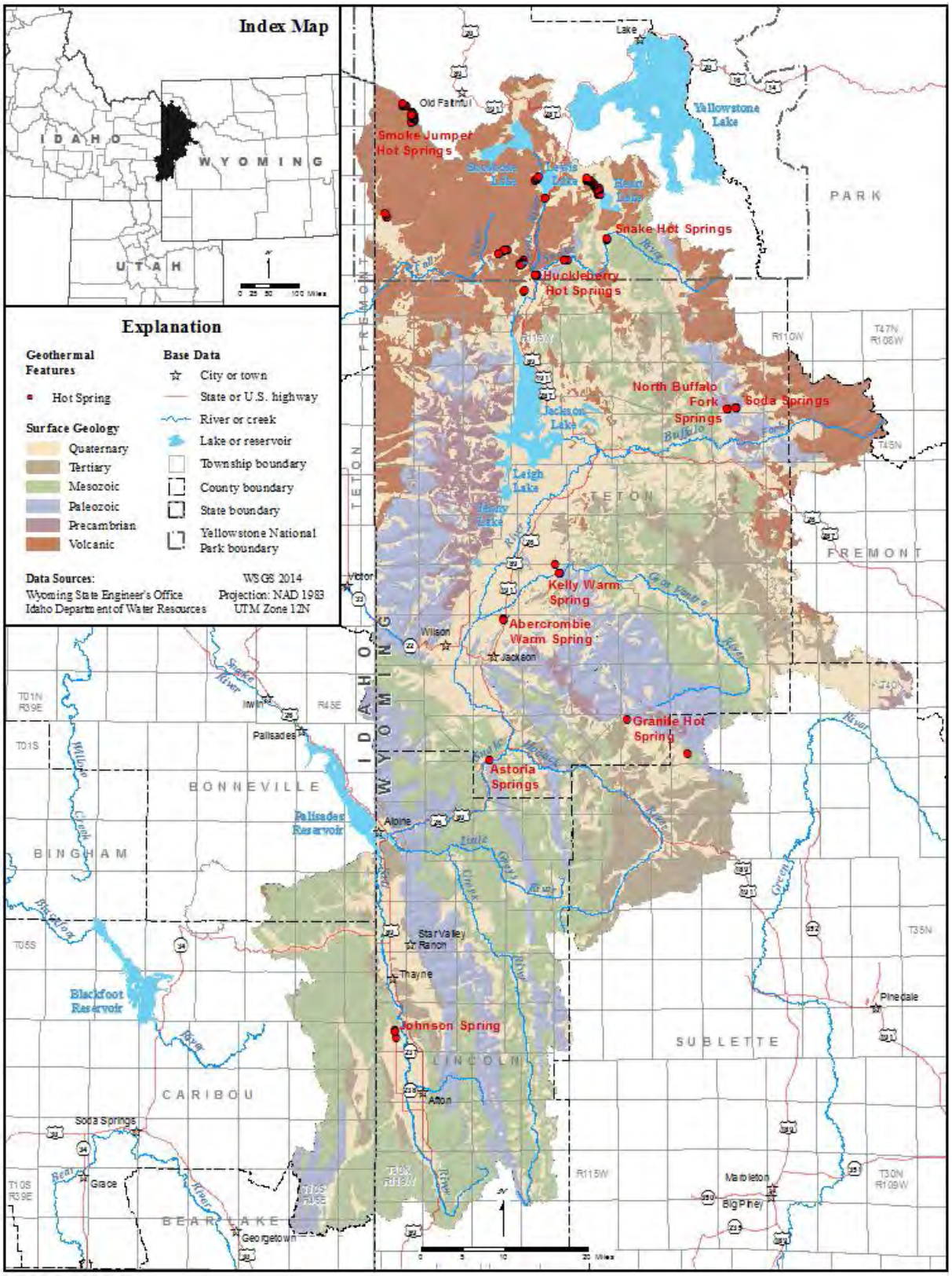


Figure 4-8. Geothermal features, Snake/Salt River Basin.

- Multiple phases of folding and faulting that involved Precambrian basement rocks.
- Folding and faulting of the Overthrust Belt during the Sevier Orogeny.
- Extension of the Basin and Range Province.
- Volcanism that created the Yellowstone Plateau and the Absaroka Range.
- Uplifted mountain ranges that surround and separate the basins, including the Gros Ventre, Teton, Wyoming, Salt River and Snake River mountains. Subsidence of structural basins including Jackson Hole, Hoback Basin, and Star Valley.

4.3 Geologic units in the Snake/Salt River Basin

Geologic units within the Snake/Salt River Basin vary widely in lithology and distribution, and range in age from Precambrian crystalline rocks to recent alluvial and terrace deposits. The legend on **plate 1** identifies the geologic units present in Snake/Salt River Basin; the individual geologic units are described in **appendix A**. The distribution of geologic units throughout the basin reflects several periods of deposition, uplift, faulting, folding, erosion, volcanism, and reworking/re-deposition of older units as younger units.

Precambrian basement rocks are exposed in the cores of the Tetons, Gros Ventre, and Absaroka mountains and are bounded by Paleozoic to Cenozoic sedimentary strata and volcanic material. The sedimentary succession of the Overthrust Belt, predominately the Wyoming, Salt, and Snake River ranges, can be divided into two main classifications: 1) a passive margin sequence ranging in age from Middle Cambrian to Late Jurassic that consists of carbonates and fine-grained clastic sedimentary strata, and 2) a clastic wedge ranging in age from Early Cretaceous to Late Tertiary strata comprised of marine and terrestrial clastic detritus. The passive margin deposits derived from successive transgressive-regressive sequences, and the clastic wedge resulted from material shedding off orogenic highlands to the west.

Volcanic material derived from the Absaroka Volcanic Province and Yellowstone hotspot that sculpted and formed the Absaroka Mountains and Yellowstone Plateau are composed primarily of basalt and rhyolite flows, tuffs, re-worked volcaniclastic material, and igneous intrusions.

Late Tertiary to Quaternary unconsolidated hydrogeologic units in the Snake/Salt River Basin include alluvial, fluvial, paludal, lacustrine and colluvial sediments; landslide deposits; glacial deposits; gravel pediment and fan deposits; and terrace gravels. The Quaternary-aged glacial deposits consist of poorly sorted clay, silt, sand, gravel. and boulders. Glacial deposits are present in the Overthrust Belt and Jackson Hole.

4.3.1 Teton Range (Smith, 1993)

The Teton Range, situated within the Middle Rocky Mountain physiographic province, is the youngest mountain range in the Rockies. The Neogene age Teton Range is superimposed over the northwest portion of the ancestral Gros Ventre Range. The Tetons are an upthrown, titled fault-block of Precambrian basement rocks and more than 5,000 feet of overlying Paleozoic sedimentary strata, including significant carbonates. The range has a vertical uplift of over 25,000 feet, inferred from the depth to basement, about 16,400 feet, underneath Jackson Hole. The Precambrian rocks exposed in the Teton Range consist predominantly of gneiss and schist, with intrusions of pegmatite granite. Exposures of metaconglomerates and metaquartzites also occur throughout the range.

The remarkable front of the Teton Range is a product of one of the most active normal faults in the Intermountain Seismic Belt (ISB) and the eastern extent of the Basin and Range Province. The Teton fault system originated as early as 5 to 13 million years ago and has been active ever since. Quaternary fault scarps, ranging from 9 to approximately 150 feet high, are exposed over 25 miles along the 33 mile length of the Teton fault. The youngest fault scarps offset Pinedale-age

(approximately 14,000 years) glacial deposits and younger alluvial and fluvial deposits.

4.3.2 Absaroka Mountains (Sundell, 1993)

The Absaroka Range is a remnant of thick volcanic and volcanic-derived accumulations erupted along a belt of andesitic stratovolcanoes. Today, the remaining deposits cover approximately 9,000 square miles in northwestern Wyoming and southwestern Montana. In the Snake/Salt River Basin, the Absaroka Range is bordered by the Bighorn Basin to the east, the Beartooth Mountains to the northeast, the Yellowstone Plateau to the north-northwest, and the Gros Ventre Range to the south. Volcanism occurred between 53 to 35 million years ago (53-35 Ma). Volcanic materials superimpose Phanerozoic sedimentary strata in the shallow foreland topographic and Laramide structural basin. The Absaroka Volcanic Province signifies the largest Eocene volcanic field in the Rocky Mountains. The Absaroka volcanic suite is composed of andesite, dacite, breccia, tuff, and re-worked volcaniclastic material (conglomerates, sandstone, siltstone, and claystone), with a maximum, combined thickness of more than 6,000 feet.

Deformation of the Absaroka volcanic rocks occurred as a result of Laramide folding and faulting, intrusive igneous activity, slope processes, and post-volcanic extension and compaction.

Some of the largest landslides ever known in Earth's history consisted of transported reworked volcanic material from the Absaroka Volcanic Province.

4.3.3 Gros Ventre Range (Horberg and others, 1949)

The Gros Ventre Range is a northwest trending, Laramide uplift that consists of a Precambrian-age basement core underlying a generally continuous Paleozoic, Mesozoic, and Tertiary sedimentary section. The range is situated just west of the Wind River Range and south of the Absaroka Mountains and is bounded to the southwest by the northwest-striking Cache Creek thrust fault, consisting of a broad asymmetrical anticline with a steep and locally faulted southwest limb (**fig. 4-1**). The western portion of the range is bounded by the Jackson Hole valley and is transected by Tertiary faults. Older structures extend to the north beneath Jackson Hole and into the Teton fault block. The range is subdivided into two asymmetric uplifts, or blocks of basement core, separated by the Granite Creek syncline: the eastern Shoal Creek block and the western Skyline Trail block. Maximum displacement occurred along the southwestern margin of the Gros Ventre Range where offset in Precambrian basement rocks indicates the greatest relative uplift.

4.3.4 Wyoming Range (Ross, 1960)

The Wyoming Range is bounded by the Hoback Basin to the east, the Green River Basin to the South, and the Gros Ventre Range to the north (**fig. 4-1**). The range is structurally bounded to west with the Salt River Range by the Absaroka Thrust sheet. Exposed shale, sandstone, conglomerate, and limestone units range in age from Middle Cambrian to Tertiary. The Wyoming Range encompasses the Darby thrust system, the easternmost and youngest thrust system of the Overthrust Belt. The primary structural features of the Darby Thrust system are the Darby, Prospect, Jackson, and Hogsback thrust faults. Sections of the Darby Thrust sheet have been overprinted by Basin and Range normal faults, predominantly, by the Hoback fault. The Hoback fault is a Mid-Tertiary high angle fault that is superimposed on previously folded and faulted Sevier structures. East of the Hoback fault, a series of imbricated thrust faults are structurally bounded by the Cache Creek thrust fault.

4.3.5 Salt River Range (Lageson, 1979)

The Salt River Range is the structural culmination of the Absaroka-St. Johns thrust complex and encompasses a complex array of imbricated thrust faults and asymmetric folds associated with/related to the Overthrust Belt system. The range is bounded by the Star Valley to the west, the Wyoming Range to the east-northeast and the Green River Basin to the east (**fig. 4-1**). The

Grand Valley fault bounds the range along the western margin where Tertiary-age units are offset against Mesozoic and Paleozoic strata. The Tertiary-age Grand Valley fault, a basin and range bounding normal fault, runs along the western margin of the Salt River Range and along the eastern margin of Star Valley forming an 85 mile long fault complex. Rock units within the Salt River Range vary from Middle Cambrian to upper Cretaceous and consisting of shale, sandstone, conglomerate, and limestones.

A parallel series of faults associated with the Absaroka thrust system are the primary structural features of this range. The Absaroka thrust system, part of the Overthrust Belt, is a 150 mile thrust sheet extending from the Snake River Plain in eastern Idaho to Salt Lake City, Utah. In the Salt River Range, the Absaroka Thrust sheet is considered to be a large-scale duplex structure bounded on the north and south by steep lateral ramps in large footwall imbricated thrusts.

4.3.6 Snake River Range (Horberg, 1949)

The Snake River Range is the northern continuation of the Wyoming and Salt River ranges and is the northern arc of the Overthrust Belt. The range is bounded by the Teton Range to the north, Gros Ventre Range to the east, and the Caribou Range, located in southeastern Idaho, to the southwest. The Snake River Range encompasses westward-dipping thrust faults and parallel folds. Although the Snake River Range includes nine, imbricate sheets of the Absaroka system, which form an overlapping array, the Absaroka, Poison Creek, and St. John thrust faults are the primary structural features of the range. The Absaroka thrust can be traced over the entire length of the Overthrust Belt. The St. John overrides the Absaroka at the north end of the complex in the Snake River Range. Rock units within the Overthrust Belt of the Snake River Range vary from Middle Cambrian to Late Tertiary. Middle Cambrian to Late Triassic age units consists of carbonates and fine grained clastics and Early Cretaceous to Late Tertiary strata comprises of marine and nonmarine clastic detritus.

4.3.7 Yellowstone Plateau (Smith, 1993)

The Yellowstone-Snake River Plain (YSRP), a 16 million-year old volcanic system that transects Nevada, Idaho, Montana, and Wyoming is one of the Earth's largest silicia-rich volcanic systems. The geology and hydrogeology is dominated by the Yellowstone hotspot. The Yellowstone-Snake River volcanic system in northwestern Wyoming is a large, silicic, Pleistocene-age volcanic field distinguished by three large calderas with a total eruptive volume of about 2,050 cubic miles. The Yellowstone Plateau, a relatively flat landscape with low, rolling mountains, accumulated from this volcanic material, rises approximately 8,200 feet high above mean sea level. The volcanic rocks from the Yellowstone area range in age from 0.6 to 16 million years old, with the oldest rocks outcropping in southwestern Idaho and northern Nevada. The Yellowstone-Snake River volcanic material within the Snake/Salt River Basin consists predominantly of rhyolite with scattered basalt flows and minor igneous intrusions.

4.3.8 Hoback Basin (Spearing, 1969)

During the early Tertiary, western Wyoming's overthrust region experienced numerous stages of uplift supplemented by synorogenic deposition of thick sediments into subsiding intermontane basins. The Hoback structural basin is a prime example of one of these sinking basins and the Hoback Formation, confined within the basin, exhibits one of these thick, early Tertiary deposits. The Hoback Basin covers approximately 315 square miles and is bounded by the Wyoming Range to the west, the Gros Ventre Range to the north north-east, and the Rim to the south (**fig. 4-1**). The Rim is a drainage divide at the northern boundary of the Green River Basin. The Hoback Formation ranges in age from Middle Paleocene to early Eocene. Structurally bounded along

the western portion of the basin, the Hoback Formation is overridden by the Jackson-Prospect thrust sheet along the Prospect fault and is folded along the Little Granite-Monument Ridge anticline. Along the western margin of the basin, the Hoback Formation has a moderate eastward dip of 40 degrees that decreases to 10 degrees at the eastern margin. On the eastern side of the basin, the units are structurally truncated by the Cache Creek Thrust fault and a small syncline along the southwestern flanks of the Gros Ventre Range. The Cache Creek thrust fault plane dips northeast, and its asymmetrical trace indicates a relativity low dip angle. The units dip towards the southwest along strike with the Cache Creek Thrust fault.
The Hoback Formation is characterized by three, major environments of deposition: thick sandstone facies; conglomerate facies; and thin, interbedded sandstone, shale, and limestone facies. The formation is wedge-shaped with the maximum basin subsidence and sedimentary axis located in the central and northern portions of the Hoback Basin. The formation is thickest (~16,000 feet) in the center of the basin and thins southward to approximately 2,500 feet where the southern boundary of the Hoback Basin meets the north end of the Green River Basin.

4.3.9 Jackson Hole (Smith, 1993)

Jackson Hole, a 44 mile long Laramide structural basin, occupies the hanging wall of the Teton fault and is covered by asymmetric, west dipping, Tertiary-Quaternary basin-fill stratigraphy. The valley is bounded by the Teton Range to the west and the Gros Ventre Range to the east (**fig. 4-1**). The Quaternary deposits in the valley consist of fluvial, alluvial, glacial, and volcaniclastic facies and are underlain by Tertiary fluvial, lacustrine, and volcaniclastic deposits. The glacial deposits in the valley provide evidence for two periods of Pleistocene glaciation known as the Bull Lake (100 to 150 thousand years ago) and the Pinedale (14 to 30 thousand years ago) periods. Several bedrock buttes, containing Paleozoic rocks, are exposed in the central and southern parts of the valley. Paleozoic units are also exposed on the eastern flank of the Teton Range.

4.3.10 Star Valley (Walker, 1965)

Star Valley consists of two half-grabens that resulted from extensional processes along the Grand Valley fault system during the Neogene. The valley is bounded by the Salt River Range to the east and the Gannett Hills in Idaho to the west. Sedimentary strata exposed along the front of the Salt River Range and Gannett Hills consist of Mesozoic age conglomerate, sandstone, limestone, and shale. Paleozoic limestone outcrops in a small butte located in the northern part of the valley. The elevation of the valley floor ranges from 6,000-7,000 feet and contains moderate slopes on the alluvial fans derived from the Salt River Range and Gannett Hills. The alluvial fans on the east side are steeper at their heads than the alluvial fans on the west side of the valley, indicating that the east side of the valley is remains structurally active along normal faults associated with the Grand Valley fault system.

Star Valley is divided into two basins because of the difference in sediment type and Quaternary displacement rates on different segments of the Grand Valley fault system. In the northern section of the valley, the Salt River Range front, geomorphic relations indicate a lower rate displacement along the Grand Valley fault than along the southern segment. The valley floor sediments in the northern section include older (early to late Pleistocene) alluvial fans and extensive Tertiary outcrops. In contrast, the southern section of the valley encompasses numerous fault scarps separating younger valley sediments from deformed Mesozoic and Paleozoic strata in the Salt River Range. Additionally, steep walled canyons, apparent range-front triangular facet spurs, and young, faulted range front alluvial fans indicate rapid basin subsidence. Pleistocene-age deposits in Star Valley consist of sand and gravel, which are the principal aquifers in the valley.

4.4 Geothermal resources

The geothermal resources of the Snake/Salt River Basin occur where groundwater exists at anomalously elevated temperatures relative to the average geothermal gradient. The hydrothermal

occurrences within the Snake/Salt River Basin are typically found at a depth that prohibits their beneficial use. Hydrothermal resources within the Snake/Salt 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., Granite Hot Springs).

Generally, groundwater heats as it flows downdip into a structural basin in accord with the local geothermal gradient. Snake/Salt River Basin hydrothermal resources occur primarily where heated groundwater rises 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 along 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 Snake/Salt River Basin. The locations of known and potential areas of hydrothermal resource development are shown on **figure 4-1**.

4.5 Mineral resources

Figures 5-4, **5-7**, **5-8**, and **5-9** show the distribution of petroleum operations and other active and historic mineral development locations within the Snake/Salt River Basin (**section 5.7.2**). Mineral development operations require the use of groundwater and may create potential avenues for groundwater contamination. Even in areas without mineral development, the presence of some naturally occurring minerals, such as those containing uranium, arsenic, and hydrocarbons, can, at significant concentrations, negatively impact groundwater quality.

Significant quantities of oil and gas have never been developed in the Snake/Salt River Basin.

Figure 5-7 shows abandoned coal, metal, uranium, phosphate, and sand and gravel mines in the Snake/Salt River Basin. Mapped coal, sand, and gravel mines are predominantly historic pit mines. A single, historic phosphate mine is located near Afton and a single uranium mine is located in the Absaroka Mountains near the Gros Ventre River. A historical metal mine is sited on the western flanks of the northern Teton Range. Currently, there is no active coal mining in the Snake/Salt River Basin. Sand, gravel, and limestone have been extensively mined within the Snake/Salt River Basin, and still are produced in some localities (**figs. 5-7** through **5-9**).

Chapter 5

Technical concepts: Hydrogeology and groundwater quality

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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. The hydrogeologist 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. Shallow 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 supply. The hydrogeology of these 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 (WDEQ) class-of-use, water-quality standards (**section 5.5.1**; **chapter 7**). Aquifer sensitivity, potential sources of groundwater, 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 is 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 (i.e., intergranular space), fractures of varying size, 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's 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 the most 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 the 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*. An aquifer system 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, and evaporites). Most aquifer systems also share the following characteristics:

- Regionally extensive,
- Common recharge and discharge areas and mechanisms,
- Similar hydraulic properties,
- Similar water-quality characteristics, and
- 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 groundwater movement between the *aquifers* it separates or between an *aquifer* and the ground surface. The *hydraulic conductivity* of a confining unit may range from essentially zero to any 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. Given large areas and extended periods of time, confining units can ultimately leak significant 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* that contains groundwater under atmospheric pressure and thus rises and falls relatively quickly in response to *recharge* (e.g., precipitation, irrigation, or waste disposal) 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 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, 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 earth materials deposited primarily by gravity at the foot of a hillslope including 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 that penetrate that aquifer. Within an *unconfined aquifer,* the conceptual surface corresponds to an actual, physical surface. *Potentiometric surface* has generally replaced the older terms *piezometric surface* and *water table*, and *groundwater surface* is a more up-to-date synonym. The *potentiometric surface* is generally mapped by equal-elevation contours in feet above mean sea level.

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. While the *capillary fringe* above the water table is saturated, it is below atmospheric pressure and thus fails to meet the definition of the water table. The term water table implies a flat, horizontal surface, but the actual surface is tilted or contoured like the land surface. In colloquial usage, the water table is the first occurrence of unconfined groundwater encountered at depth 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 drawn upward by this effect.

Vadose zone – the depth interval between the ground surface and the water table that can include: 1) unsaturated soils, unsaturated bedrock, and unconsolidated materials such as alluvium, *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 neither the well nor surrounding wells are being pumped and the *total head* in the aquifer is generally at equilibrium. Static head/ water level is commonly expressed in feet of elevation above mean sea level.

Drawdown – the lowering of the groundwater potentiometric surface (total head) by discharge from an aquifer (pumping or natural outflow) 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 or hydrogeologic 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) 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 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 (often expressed as 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. This parameter can vary in any direction, but 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 *total head*. Like *specific yield*, storage coefficient is a dimensionless parameter—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, also 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 flow – occurs 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, downstream flow.

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). Generally mg/L is equivalent to 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 some combination of these three types:

- *Porous flow* occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone, or unconsolidated deposits) 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. 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,* i.e., the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the rock matrix.

- *Conduit flow* occurs through large, discrete openings (pipes, cavities, channels, caverns, and other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite, or halite. 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 and joints developed during structural deformation (folding, faulting), expansion (rapid overburden erosion) or compaction, (rapid deposition), physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation) or thermal contraction (fractured and columnar basalts). 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 groundwater 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 parameters to accurately quantify. Recharge cannot be measured directly, but is estimated indirectly using tools such as chemical or heat tracers, water budget calculations, or groundwater level analyses (Healy and Scanlon, 2010).

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (**fig. 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. During those times, 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 basin interiors 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, water flows overland to be stored on the surface in puddles (depression storage) or to discharge to streams. In the latter 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

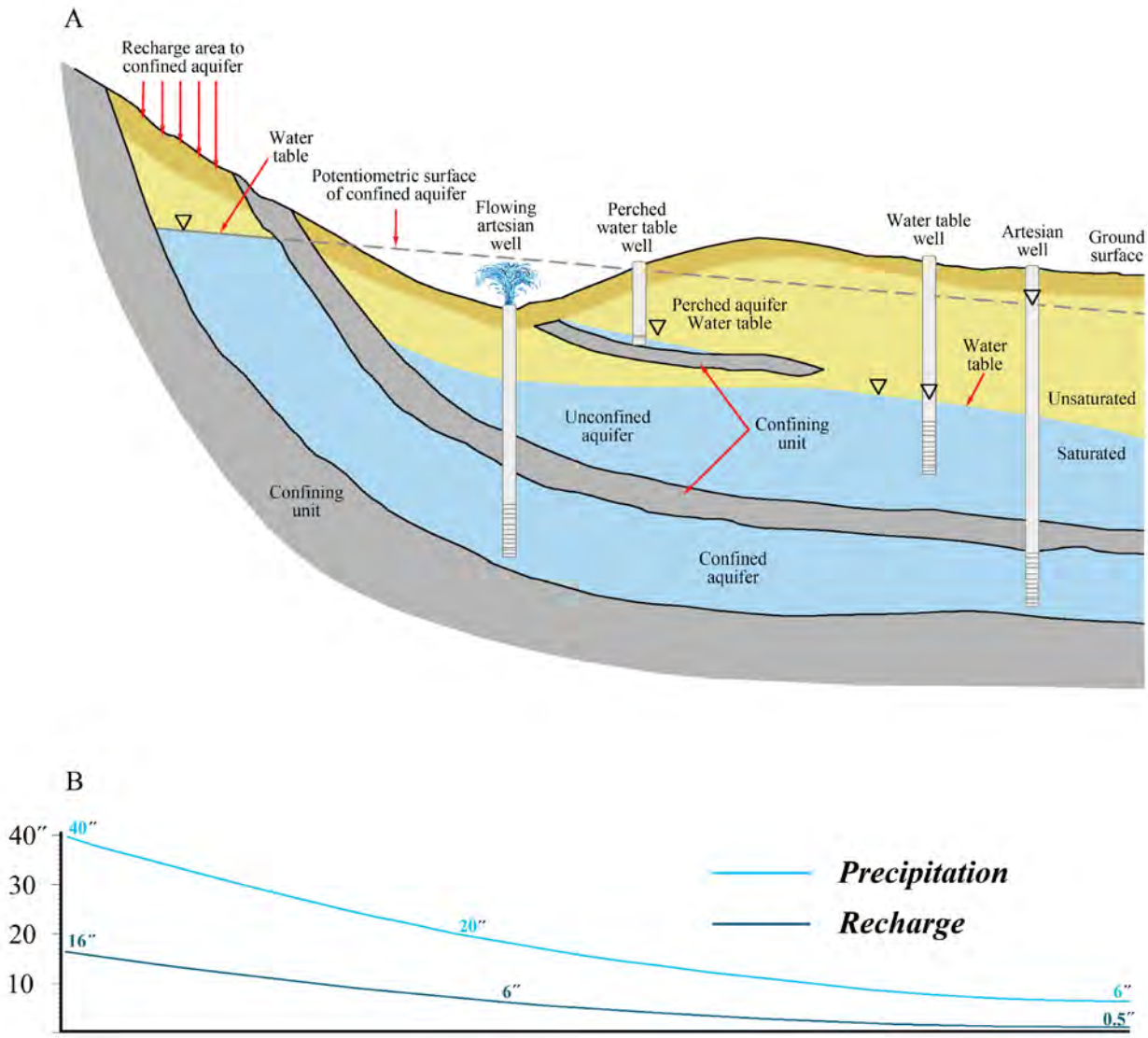


Figure 5-1. Conceptual cross-section of typical groundwater features that occur in Rocky Mountain structural basins and synclinal features. Older hydrogeologic units outcrop and recharge at margins, dip steeply (basinward), and become confined within short distances. Potentiometric surfaces for unconfined aquifers are marked with inverted triangles (▽) (water tables) and as a dashed line extending down-dip 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 recharge profile, in inches, basin margin to basin center. Adapted from WWC Engineering and others, 2007.

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: 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 bedrock fractures;
- Large openings, both natural (karst, animal burrows) and man-made (mines, pits, well-bores);
- Geospatial distribution, capacity, and permeability of surface depressions;
- Opportunity for recharge from surface waters; and
- Local land use (irrigation, soil stripping, paved areas).

In addition to infiltration from the surface, an aquifer may also receive recharge as leakage from adjacent confining units. Although recharge may flow very slowly from confining unit to receiving aquifer, the volume of leakage can be quite substantial over time provided the geospatial contact area between the two units 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 Snake/Salt River Basin. The extent of artificial recharge is difficult to evaluate on a regional basis, but might be determined for small watersheds.

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. In 1998, the Spatial Data and Visualization Center (SDVC) at the University of Wyoming conducted a statewide recharge evaluation using geospatial analysis. The SDVC published the results in the *Wyoming Groundwater Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998). Originally, the SDVC calculated average annual recharge for the 1961 – 1990 period of record by:

- 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; and
- 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,
  - increases as precipitation increases,
  - increases as the sand content of the soil increases, and
  - 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.

This study used the SDVC approach (Hamerlinck and Arneson, 1998) to estimate average annual

recharge in the Wyoming portion of the Snake/ Salt River Basin (**chapter 6**) for the 30-year period of record from 1981- 2010. The analysis used two geospatial datasets: 1) percolation percentages for documented soil/vegetation combinations (**fig. 6-5**) published in the Hamerlinck and Arneson (1998) study, and 2) average annual precipitation (**fig. 3-3**) from 1981 through 2010 (PRISM, 2013). **Figure 5-2** shows average annual recharge for the 1981 – 2010 period of record; this information is summarized in **tables 6-1 – 6-3**.

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 (baseflow) into streams, wetlands, lakes, and other surface waters, 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 total natural discharge is difficult to determine, especially on a basin-wide basis. While some forms of discharge, such as visible surface flows from springs, are readily measured, others are difficult to quantify because they are concealed (leakage between geologic units, subsurface flows in streambeds--i.e., hyporheic flows--or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). Discharges that cannot be measured directly must be estimated through proxy calculations. For example, using a mass balance (water balance) model can refine estimates when information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available, as is the case in this study (**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. Groundwater withdrawals for beneficial use are estimated in the previous water plan (Sunrise Engineering, 2003) and are discussed in **chapter 8**.

Groundwater discharge, buffered by the storage function of an aquifer, is generally more efficient than recharge. 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 basin in question. Reasonable estimates of both recharge and discharge provide valuable baseline data to evaluate the sustainability of any groundwater development project.

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 prevails 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 deeper aquifers. The arrangement of aquifers and confining units that store and convey groundwater constitutes the structural framework of the hydrogeologic system within a 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 (**fig. 5-1**) and some springs that discharge groundwater from deep aquifers. 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. Conversely, high-permeability units, where friction is low, generally exhibit low hydraulic gradients. The slope (gradient) of a potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where the resistance to flow in any direction is negligible and the gradient is virtually 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 Snake/Salt 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 Snake/Salt River Basin occurs primarily in areas where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeter of the basin. These aquifers are unconfined at the outcrop areas, but as groundwater flows downdip from the recharge areas into the basin, 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 Snake/Salt River Basin is primarily controlled by structure and stratigraphy. Major aquifers and aquifer systems in the Snake/Salt 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 Snake/Salt River Basin is predominantly through permeable formations down-gradient from higher to lower hydraulic pressure. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage, safe yield, and sustainable development

In addition to functioning as the conveyance system for groundwater flow, the saturated geologic units that compose the aquifers of the Snake/Salt River Basin also store enormous volumes of groundwater. Understanding groundwater

storage and how to develop groundwater resources in a particular area of interest without depleting storage and natural discharges to unacceptable levels are considered in most development projects. In this section, the basic technical concepts of groundwater storage and the environmental aspects of the "safe yield" concept are discussed. In fact, acceptable (or unacceptable) levels of groundwater depletion are frequently defined administratively by state law, court order, international treaty, or interstate agreements.

Two important aspects of groundwater resource assessments on any scale are 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 used beneficially. Technical, financial, and legal factors determine what fraction of the total volume of groundwater stored within a particular aquifer can be considered an available resource. Initially, development costs, water rights considerations, and water quality requirements are three primary factors that are evaluated to 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 5.5** 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)**. Important hydraulic properties with respect to the sustainable development of groundwater resources are related to the storage coefficient of the material that composes an aquifer, particularly specific yield for unconfined aquifers and specific storage for confined units.

5.1.4.1 Groundwater storage

The concept of storage coefficient can be applied to both unconfined and confined aquifers. 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 a percentage or decimal fraction.

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, also expressed as a percent (or decimal fraction) of the unit volume, 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). Because capillarity is higher in fine-grained materials which have 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. The sum of specific retention and specific yield is equal to porosity. Highly productive unconfined aquifers are characterized by high specific yields.

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, after which the storage coefficient is essentially equal to the specific yield.

To some extent, the groundwater stored in an aquifer can operate as a buffer between recharge, natural discharge and withdrawals, 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 from over pumping, however, can reduce aquifer water levels to the point where recharge is induced, 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 storage depletion and compression of the aquifer material.

5.1.4.2 Safe yield

The term "safe yield" is used to describe the rate of groundwater production that can be sustained without causing an unacceptable level of depletion of storage volume or other adversities, such as degradation of groundwater quality or depletion of surface water flows. In the past, safe yield estimates were tied to average annual recharge rates and were thought to predict aquifer responses to long-term withdrawals and recharge inflows. Safe yield estimates have been applied over a wide range of scale, from individual wells to entire structural or drainage basins. The concept of safe yield originated in the early twentieth century with engineering studies of surface water reservoirs.

The concept was subsequently applied to groundwater resources. Lee (1915), in his article, *The Determination of Safe Yield of Underground Reservoirs of the Closed Basin Type*, first described safe yield as, "the limit to quantity of water that can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Lee noted that safe yield… "is less than indicated by the rate of recharge, the quantity depending on the extent to which soil evaporation and transpiration can be eliminated from the region of groundwater outlet." Meinzer (1923) placed it within the context of economics when he defined safe yield 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. The definition given by Fetter (2001) includes these factors,

> "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."

Two notable misconceptions that arose in early discussions of the safe yield concept persist to this day. The first is that groundwater withdrawals from wells and springs are sustainable as long as they do not exceed the amount of annual recharge in a particular area. A second, persistent belief

follows from the first; developing a water budget will determine a "safe" amount of groundwater development.

Theis (1940) concisely addressed the misconception relating safe yield to annual recharge levels by identifying the sources of water for groundwater development,

> "…under natural conditions…previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge or by loss of storage or by a combination of these."

The scientific literature has continually supported Theis' observations since then. In brief, the amounts of groundwater withdrawn by new development projects initially come from storage depletions and then gradually transition to induced recharge of surface water (stream flow depletions). In the best case, the newly developed groundwater system will reach a new state of dynamic equilibrium over time but this includes, by necessity, depletions of streamflow or groundwater storage or both. Thorough explanations of these concepts can be found in Sophocleous (1998) and Barlow and Leake (2012).

In the past, when it was thought that the upper limit of an aquifer's safe yield was determined by the amount of annual recharge, the sustainability of groundwater development was frequently analyzed by a conservation of mass approach variously referred to as a water balance, hydrologic budget, or water budget. 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)

By application of this equation, recharge rates could be estimated by making reasonable estimates of natural discharges and groundwater withdrawals from wells if it is assumed that there was to be no change in storage. The recharge estimates were then used to determine the upper limit of an aquifer's safe yield.

Average annual recharge rates for the Snake/Salt 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 Snake/Salt River Basin was prepared for this study (**chapter 8**) using information provided in the previous Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) 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 which should be used to:

- Provide a comparison of estimated groundwater withdrawals to estimated levels of natural discharge and recharge;
- Emphasize the mass balance aspect of water resources that is, "water in" (recharge) equals "water out" (natural discharges and artificial withdrawals);
- Develop further understanding of the groundwater/surface water system of the basin, and;
- Stimulate discussion among stakeholders of what constitutes sustainable yield (**section 5.1.4.3**) in the Snake/Salt River Basin.

Practically, it is unlikely that a unique and constant value of safe yield can be calculated accurately on the basin scale because of a number of limiting physical and temporal factors.

- Drainage basins cannot be treated as homogeneous underground reservoirs but are complex systems of aquifers and confining units that possess, instead, high levels of geological and hydrological heterogeneity. For example, a large drainage basin such as the Platte River (Taucher and others, 2013), may contain several structural basins, wholly or in

part. Because of these complexities, the understanding of key factors such as basin geometry and structure, hydraulic relationships between basin hydrogeological units, and deep basin hydrodynamics is largely absent within a regional model.

- Aspect(s) of spatial scale must be considered. An analysis of total groundwater uses over a regional scale, such as a river basin, may indicate that groundwater withdrawals constitute a small percentage of calculated annual recharge and imply that water resources are not over-utilized. A regional analysis may, however, conceal local scale groundwater storage depletions that have become problematic. Again, in the case of the Platte River Basin (Taucher and others, 2013), a basin wide water balance determined that recent annual consumptive uses of groundwater constitute about 13 percent of mean annual recharge. From this analysis, a safe yield evaluation would conclude that groundwater storage levels in the basin are relatively secure. In fact; some areas of the High Plains aquifer in Laramie County have seen maximum water level declines of 25-50 feet since 1950 (McGuire, 2013).

- Sufficient datasets required to make such estimations have not been obtained in most drainage basins for a number of reasons. First is the expense of collecting adequate hydrogeologic data from an acceptably sized sample set. The problem is further exacerbated in lightly populated rural areas where groundwater wells are sparsely distributed. There, adjacent sampling points (wells) are frequently separated by miles of unpaved roads, inaccessible during winter and early spring months. Second, wells are most likely sited in hydrogeologic units where the probability of successful completion is highest. Thus the available hydrogeologic data is skewed toward over-represented productive areas and away from less productive units where few wells are drilled. For example, 65 percent of likely producing wells of all types are sited on Quaternary Alluvial units which comprise 20% of basin surface area (**table 6-3**). The remaining wells (35 percent) are sited in bedrock aquifers (**figs. 8-1** through **8-4**).

- Hydrologic inputs (recharge) and outputs (discharges) are not delivered instantaneously and, in most cases, have not been accurately measured. Similarly, changes in storage are dependent on aquifer response times that can range from days to hundreds of years (Sophocleous, 2005). Thus, currently observed changes in storage may reflect present day discharges superimposed on recharge 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.

5.1.4.3 Sustainable development

The concept of sustainable development has received increasing attention in the international water resources community since it first appeared in the early 1980s. The World Commission on Environment and Development defined sustainable development as, "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In the U.S., sustainable development of water resources continues to grow in importance in light of USGS studies documenting widespread groundwater storage declines in the U.S. (Konikow, 2013; Bartolino and Cunningham, 2003) and the related effects of surface water depletion and land subsidence (Galloway and Burbey, 2011), most notably in the arid and semi-arid western states.

The American Society of Civil Engineers (ASCE, 1998) define sustainable water systems as, "… those designed and managed to fully contribute

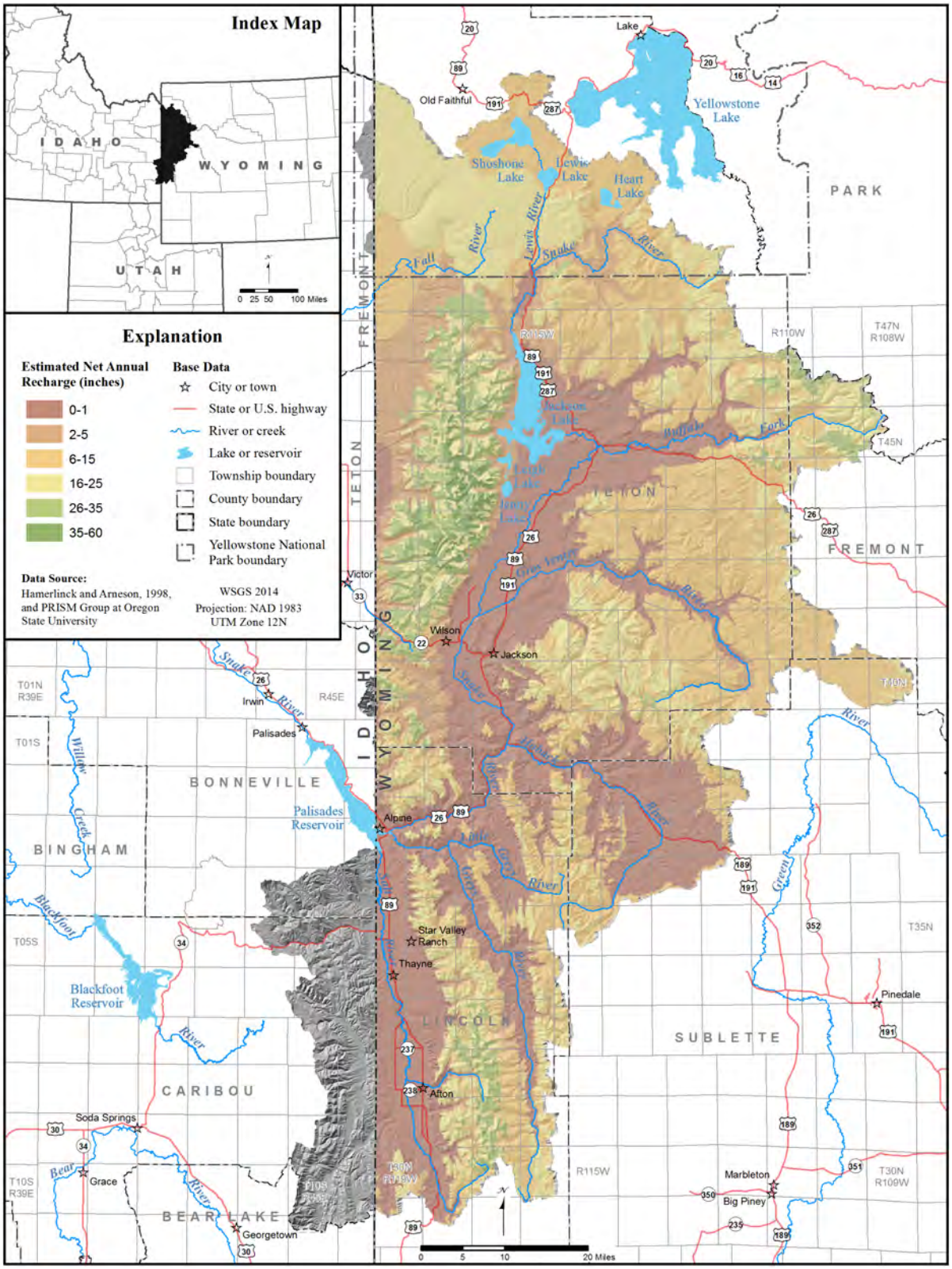


Figure 5-2. Estimated net annual aquifer recharge, in inches, Snake/Salt River Basin, Wyoming.

to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." The list of factors that affect the planning and development objectives of any water resource system is extensive. Water planners are required to consider current and future water demands, population, land use, climate, public opinion, water resource utilization, technology, and hydrologic science. Given the uncertainties encountered in these analyses, it is likely that no constant single value of sustainable yield can be developed for a particular project. The determination of sustainable yield is not a single set of calculations but a process that will require periodic reevaluation as the design elements change with time (Maimone, 2004).

Sophocleous (1998) describes a six step procedure first proposed by Mandel and Shiftan (1981) to estimate the sustainable yield of an aquifer:

1. Determine mean annual recharge.
2. Identify the first unacceptable affect that will occur as water levels are lowered. This may be defined as a physical constraint (depletion of measured springflow), or a violation of government regulations (infringement on senior water rights, mandated in-stream flows, or provisions of an interstate compact).
3. Define the quantitative relationship between water levels and the timing and extent of the unacceptable affect previously identified. This step may use widely known mathematical functions or the development of groundwater models that apply over wide areas of the aquifer or to a few critical locations only.
4. Determine minimal acceptable water levels for the aquifer or for the critical areas of interest.
5. Calculate the rate of natural discharge that will result when a new state of dynamic equilibrium consistent with the minimal water levels is established.
6. The sustained yield is the difference between Steps 1 and 5.

To this, a seventh step might be added, *"Review and reevaluate yield estimates as water demands, population, land use, climate, public opinion, water resource utilization, technology, hydrologic understanding of the system, and available alternate water sources change with time."*

The concept of *sustainable development* recognizes the ultimate sources of groundwater withdrawals defines the first unacceptable effect(s) of storage and surface flow depletions, establishes minimal water levels that ensue from those depletions and calculates the rate of diminished natural discharge. Still, if integrated into any groundwater development program, the results of sustainable yield calculations must be supported by a long term monitoring plan that utilizes an adaptive management approach. Barlow and Leake (2012) discuss, in depth, the challenges of designing, conducting, and analyzing the results of a streamflow depletion monitoring program.

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

The geologic framework for the Available Groundwater Determination Technical Memorandum for the Snake/Salt 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 provide the plumbing system for the recharge, storage, and flow of groundwater. 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.

The North American Stratigraphic Code (2005) 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 accompanying 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 chart contained in **plate 5**.

The Snake/Salt 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 Snake/Salt 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 chart are discussed in detail in **chapter 7** regarding their component geologic or lithostratigraphic units.

Plates 4, 5, and **6** provide hydrostratigraphic information from previous studies so that informed readers can track the historical development of understanding the basin's hydrostratigraphy. The hydrostratigraphic chart is 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 Snake/Salt 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 constructed 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 is 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 presented within this and other reports. Computerization greatly facilitated the process of organizing the GIS geologic units into hydrogeologic units and the construction of the surface hydrogeology map

(**pl. 2**) and associated hydrostratigraphic charts. 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 Snake/Salt River Basin.

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering 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 Snake/Salt River Basin. Under favorable conditions these aquifers can provide well yields of 500-2,000 gallons per minute (gpm). Yields are generally lower where the deposits are either thin, contain abundant fine-grained material, 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: 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 valleys, the sandstone aquifers are mostly horizontal and some are widespread. Relatively thick sandstone sequences that compose the Tertiary Salt Lake aquifer system and the Mesozoic Nugget aquifer are the most productive sandstone aquifers in the Snake/Salt River Basin. Older Mesozoic sandstone aquifers exposed by erosion along the ridges and flanks of the Snake/Salt River Basin highlands commonly dip to the west (**pls. 1** and **2**) and may contain accessible groundwater resources for several miles downdip of the outcrop areas. Groundwater quality tends to decrease with increasing depth. Some sandstone aquifers may 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. 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. Well production rates are highly variable in limestone aquifers. 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. In the Snake/Salt River Basin, these aquifers are exposed primarily along the ridges and flanks (**pl. 2**) of highlands where the upthrown sides of thrust faults have been eroded away to expose carbonate formations. The potential for vigorous recharge and groundwater circulation in Paleozoic carbonate aquifers is highest in outcrops located along flanks of the Salt River, Wyoming, Gros Ventre, and Teton ranges. In Wyoming, examples of major carbonate aquifers

include the Madison, Tensleep, and Bighorn formations. Depending on the degree of enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles downdip 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.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). 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 confining shales 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 are the basal confining unit below the sedimentary basins and 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 and others, 2007; fig. 4-9) classified the Snake/Salt River Basin geologic units; the more common names used in the framework water plan for time equivalent stratigraphic units are noted in parentheses:

Major Aquifer - Alluvial
- Quaternary alluvium

Major Aquifer – Sandstone
- Teewinot and Salt Lake formations
- Nugget Sandstone

Major Aquifer - Limestone
- Tensleep Sandstone and Minnelusa Formation
- Madison Group and Bighorn Dolomite

Minor Aquifer
- Quaternary non-alluvial deposits
- Twin Creek and Thaynes limestones
- Frontier Formation
- Phosphoria Formation and related rocks

Marginal Aquifer
- Volcanic rocks
- Camp Davis, Colter, and Hoback formations
- Sohare, Harebell formations
- Aspen and Bear River formations
- Woodside Shale and Dinwoody Formation

Major Aquitard (Confining Unit)

Cody Shale, Niobrara Formation, Steele Shale, and Baxter Shale

Precambrian 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 by this study for the Snake/Salt River Basin. Correlations between the 2007 Wyoming Statewide Framework Water Plan aquifer classification system (WWC Engineering and others, 2007), and the hydrogeology presented in this study are explained on **plates 4** through **6**.

5.4 Groundwater circulation in the Snake/Salt River Basin

The complex geologic setting of the Snake/Salt River Basin was introduced in **chapter 3** and discussed in detail in **chapter 4**. Unlike other large Wyoming river basins where one regional structural setting dominates, the Snake/Salt River Basin overlies five structural regimes: Thrust Belt structures in the south, the Absaroka and Yellowstone/Snake River Plain volcanic systems to the north, Laramide and later aged uplift structures to the north and east, and Basin and Range Province structure to the west (**chapter 4**; **pl. 1**, and **fig. 4-2** through **4-7**). The following sections discuss groundwater circulation in Quaternary, Thrust Belt, Laramide structural, and volcanic aquifers.

Fault and fracture zones control groundwater circulation in Thrust Belt, Laramide structural, and volcanic aquifers by acting as hydraulic barriers or conduits for groundwater. The effects that a particular set of faults or fractures exerts on groundwater flow can be complex. Numerous physical characteristics of the fault or fracture set, such as its type, spatial extent, deformation type and history, aperture (size of its openings), fluid chemistry and reactions, and orientation, can affect the direction and magnitude of groundwater flows. Other factors that can modify groundwater circulation include the geospatial, hydraulic, and lithologic properties of the rock units that the fault transects and also the fault's proximity, hydraulic connectivity, and spatial relationship to other faults and fracture sets.

Faults most often act as barriers that impede the flow of groundwater across strike in two ways. First, relatively impermeable rocks can be juxtaposed with more permeable units in the adjacent fault wall by the vertical displacement of stratigraphic units. Second, during the formation of the fault, friction between moving fault walls can grind rocks into clay-like, fine-grained, low-permeability sediments. These deposits, called fault gouge, fill in the spaces between the adjacent fault walls forming a fault core that impedes the flow of groundwater. In either case, the flow of groundwater can be redirected either horizontally, along the strike of the fault, or vertically depending on the hydraulic pressure gradients of the surrounding aquifers and confining layers. Many of the springs in the Snake/Salt River Basin occur along normal faults where horizontal groundwater flow has been disrupted and redirected upward to the surface under artesian conditions (**fig. 5-1** and **pl. 3**).

The presence of a fault can also increase the flow of groundwater especially in the damage zones that flank the fault's core. The small faults, fractures, veins, and folds that typically form the damage zones may extend for hundreds of feet on either side of a large fault and can act as groundwater conduits that have hydraulic conductivities which are several orders of magnitude higher than the surrounding host rock. If the damage zones are hydraulically connected to a network of other faults, they can convey water to springs and wells from areas that cover several square miles. The hydrogeologic heterogeneity created by faults can make it difficult to accurately determine the dominant patterns of groundwater circulation in heavily faulted regions, even in areas where numerous monitoring wells exist. This difficulty is exacerbated in many parts of the Snake/Salt

River Basin where bedrock wells are sparse. Thus, groundwater patterns are not well understood in those areas.

5.4.1 Groundwater circulation in Quaternary aquifers (Nolan and Miller, 1995)

In terms of the volume of water withdrawn and the number of wells permitted, the most widely used aquifer system in the Snake/Salt River Basin is the Quaternary alluvial aquifer that lies along the Snake and Salt rivers and their tributaries (Sunrise Engineering, 2003). Nearly all of the basin's irrigation wells (**fig. 8-1**), as well as most of the wells permitted for livestock (**fig. 8-2**), municipal (**fig. 8-3**), and domestic (**fig. 8-4**) uses, are located within the Quaternary system. Nolan and Miller (1995) report that the alluvial aquifer system is recharged primarily by direct infiltration of precipitation, discharge from bedrock aquifers, recharge from irrigation, and infiltration of streamflows in losing reaches of headwater streams. Evapotranspiration, groundwater discharges into surface water flows, and withdrawals from wells constitute the principal forms of aquifer discharge. Groundwater flows within this system generally follow the topography of the watershed drainages, that is, toward or parallel to the channels of the Snake/Salt River and its tributary streams (Nolan and Miller, 1995).

5.4.2 Groundwater circulation in Thrust Belt aquifers (Ahern and others, 1981)

Tertiary, Mesozoic, and Paleozoic bedrock aquifers are exposed on the flanks of the mountain ranges that border the Salt River. The Tertiary aquifer group is extensively utilized and includes the Salt Lake, Wasatch, and Evanston aquifers. Ahern and others (1981) note that groundwater circulation in these aquifers is primarily controlled by local topography and that artesian discharge is common only along stream drainages.

Recharge to these aquifers consists of infiltration of rainfall and snowmelt and streamflow seepage in ephemeral streambed reaches. Natural discharge occurs primarily at gravity-driven springs and seeps (**pl. 3**) and as direct flows into alluvial sediments.

Ahern and others (1981) noted that groundwater circulation in highly fractured, Mesozoic and Paleozoic aquifers is heavily controlled by faults and fracture sets especially in the Salt River drainage, where numerous north-south parallel systems of reverse and normal faults occur (**pl. 1**) typically in relatively close proximity to one another.

5.4.3 Groundwater circulation in Laramide structures (Huntoon 1983a, 1983b, and 1993)

Huntoon (1993) summarized a conceptual model for "The Influence of Laramide Foreland Structure on Modern Groundwater 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. Their central thesis 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 Paleozoic and lower Mesozoic carbonate aquifers exposed along the major uplifts in Wyoming foreland basins. The main components of this conceptual model include:

- 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 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 structural basins.

- Groundwater circulation is not only controlled by Laramide structures, but also alters their hydrogeology:
  - 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., the 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 dissolution-enhanced, highly anisotropic permeability. Where extensional fractures develop, their 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 parallel or oblique to the folds.
  - Large-displacement thrust faults and smaller 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 both the hanging and footwall of major uplift-bounding, large-displacement faults.
  - Within synclinal folds the rocks are highly compressed, interstitial porosity is destroyed, and fractures are compressed rather than opened.
  - Faults can act as either conduits or barriers to flow depending on…. (structural regime, diagenetic/ cementation history, connectivity between hydrogeologic units, relationship to other, proximal faults, relationship to inherited—ancestral—structures they overprint, etc.).

- 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.

- Intercrystalline permeability in major carbonate aquifers is generally very low.

- Groundwater circulation primarily parallels 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 ductile, 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 deeper, carbonate aquifers are exposed at generally higher elevations in surrounding mountain ranges.

- Large production from 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 a significant confining unit covers carbonate aquifers. 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 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.

- Synclines 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 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 facilitated the successful completion of groundwater development projects throughout the state. Clearly, identifying and mapping structures in targeted groundwater prospects is an important aspect of any groundwater exploration project including those within the Snake/Salt River Basin. Groundwater circulation in the major aquifer systems of the Snake/Salt River Basin is discussed further in **chapter 7**. Several of the components of the conceptual model described above are illustrated in **figure 5-1**.

5.4.4 Groundwater circulation in volcanic aquifers (Cox, 1973)

Volcanic aquifers constitute the most areally extensive, bedrock aquifer exposures in the portion of the Snake/Salt River Basin confined within the boundaries of Yellowstone National Park (**pl.**

1). Extensive volcanic exposures are found also in northeastern and northwestern Teton County and in northwestern Fremont County. With the exception of northwestern Teton County, few wells are completed in volcanic aquifers (**figs. 8-1** through **8-7**) because most volcanic units outcrop within wilderness areas. Volcanic units, composed primarily of basalt and rhyolite flows, tuffs, re-worked volcaniclastic material, and igneous intrusions (**chapter 4**), were deposited during two episodes of volcanism. The Eocene volcanic period that occurred between 35 to 53 million years ago (Ma) formed the Absaroka Volcanic Province, now located in the northeastern Snake River Basin. A more recent (0.6 Ma to 16 Ma) volcanic period created the Yellowstone Plateau.

Cox (1973) noted that brecciated zones at the contacts of individual extrusive flows, heavily fractured units and volcanic rocks with high levels of well-connected vesicular porosity, exhibit the most vigorous groundwater circulation and are capable of discharging "a few tens of gallons per minute." Wells and springs in volcanic aquifers that lack these features generally yield "only a few gallons per minute." Natural recharge to volcanic aquifers consists of infiltration by precipitation and snowmelt, streamflow seepage in ephemeral streambed reaches, and inflows from adjacent aquifers. Natural discharges occur at gravity driven springs and seeps (**fig. 7-2**) and as direct flows into alluvial sediments. **Figure 7-2** shows the locations of springs, wells, and associated physical and chemical characteristics within the context of the generalized geology for the Snake/Salt River Basin in Wyoming and tributary areas in Idaho. **Plate 3** lists spring discharge, well yield, and other hydraulic data for nine wells and 46 springs sited in undifferentiated volcanic units. While spring discharges range from 0.8 to 449 gpm, the median value of 3.7 gpm is indicative of the generally low rates of discharge from volcanic aquifers.

5.5 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 primarily depend on water quality. For this study, the USGS compiled groundwater quality data for the Snake/Salt River Basin hydrogeologic units (**section 5.6**) from several sources. These data confirm that the best quality groundwater is generally found in regions closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulating through or residing in the aquifer.

Factors that affect groundwater quality include the type 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 Snake/Salt River Basin than to the major aquifers, within which groundwater circulation is relatively (often substantially) more vigorous. Groundwater quality in the Snake/Salt River Basin varies from fresh water, with total dissolved solids (TDS) less than 1,000 mg/L (ppm) that is suitable for any domestic purpose, to briny, deep, oil field aquifers unsuitable for virtually any use, with TDS greater than 300,000 mg/L.

In the absence of irrigation, most alluvial aquifers receive recharge from hydrologically connected streams and underlying or adjacent bedrock. Irrigation can dominate recharge when application is active. Direct precipitation can also add to recharge but due to high evapotranspiration rates in the interior lowlands, 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 unconsolidated 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 recharge 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 salts. 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 Snake/Salt 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 sulfate, and chloride dominates 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.

Section 5.5.1.3 contains 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 Snake/Salt River Basin aquifers and their component geologic and lithostratigraphic units is provided in **chapter 7.**

5.5.1 Groundwater quality

This section describes groundwater quality for the Snake/Salt River Basin. Specifically, this section addresses how data on chemical constituents for the Snake/Salt River Basin groundwater study were accessed, compiled, screened, and statistically summarized.

5.5.1.1 Regulation and Classification of Groundwater

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, regulates the public water systems located within the state. Each agency has established groundwater standards, and revises and updates them periodically.

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* (http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf), 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 water 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.

5.5.1.2 Standards of groundwater quality

In this 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 (WSGS **table 5-2)** and summary statistics for environmental and produced water samples tabulated by hydrogeologic unit as quantile values (**appendices E-1** to **E-6**). In assessing suitability for domestic use (USEPA health-based standards of Maximum Contaminant Levels (MCLs) and Health Advisory Levels (HALs) are used as guides (however, these standards are not legally enforceable for any of the sampling sites used in this study). The USEPA Secondary Maximum Contaminant Levels (SMCLs), which generally are aesthetic standards for domestic use, and WDEQ Class II groundwater standards for agriculture, Class III standards for livestock and Class IV standards for industry are used as guides for assessing suitability.

Many groundwater samples used in this study were not analyzed for every constituent for which a standard exists. In this report, the assessment of suitability of water for a given use is based *only* on the concentrations of constituents determined; the concentration of a constituent not determined could possibly make the water unsuitable for a given use.

Water-quality concentrations are compared to three types of USEPA standards: MCLs, SMCLs, and lifetime HALs. The USEPA MCLs (U.S. Environmental Protection Agency, 2012) 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. The MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. The MCLs, however, a valuable reference when assessing the suitability of water for these uses.

The USEPA SMCLs (U.S. Environmental Protection Agency, 2012) 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. Lifetime HALs are based on concentrations of chemicals in drinking water that are expected to cause any adverse or carcinogenic effect over a lifetime of exposure (U.S. Environmental Protection Agency, 2012) and will be reffered to as HALs in the remainder of the report. Because of health concerns, the USEPA has proposed two drinking-water standards for radon (U.S. Environmental Protection Agency, 1999)— an MCL of 300 picocuries per liter (pCi/L) and an alternative MCL (AMCL) of 4,000 pCi/L for communities with indoor air multimedia-mitigation programs. Radon concentrations herein are compared, and exceedance frequencies calculated, in relation to the formerly proposed MCL of 300 pCi/L and the formerly proposed alternative AMCL of 4,000 pCi/L.

Water-quality standards for Wyoming Class II, Class III, and Class IV groundwater (Wyoming 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 watering. Class IV groundwater is water that is suitable for industry. The Class IV TDS standard (10,000 mg/L) 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.

5.5.1.3 Sources, screening, and selection of data

Groundwater-quality data compiled through 2011 were gathered from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/wy/nwis/qw/), the USGS Produced Waters Database (PWD) (http://energy.cr.usgs.gov/prov/prodwat/), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (http://wogcc.state.wy.us/), the University of Wyoming Water Resources Data System (WRDS) database (http://www.wrds.uwyo.edu/wrds/dbms/hydro/sel.html), 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. Groundwater-quality sample locations retained after data screening, and used herein, are shown in **figure 7-1**.

Many of the groundwater sites in the Snake/Salt River Basin 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. 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 dataset.

Chemical analyses of groundwater-quality samples available from the USGS PWD were included in the dataset used for this report. Produced water is water co-produced with oil and gas. The PWD includes samples within the Snake/Salt River Basin. Only those PWD samples from a wellhead or from a drill-stem test were included in the dataset. Samples that had not been assigned to a hydrogeologic unit were removed from the dataset. 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. The PWD documentation 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, some sample analyses may have reported the sum of sodium and potassium concentrations as sodium concentration alone.

Chemical analyses of groundwater-quality samples available from the WRDS database were included in the dataset used for this report when information was available to identify the hydrogeologic unit, locate the spring or well, and the site was not included in the USGS NWIS database. In addition, WDEQ monitoring wells located at sites of known or potential groundwater

contamination were removed from the dataset 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 dataset.

Groundwater quality in the Snake/Salt 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 outcrop areas increases and (residence time increases). Correspondingly, the water quality in a given hydrogeologic unit generally deteriorates with depth.

Some of the water-quality samples from aquifers in Quaternary- and Tertiary-age hydrogeologic units came from wells and springs that supplied 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, it generally is not used for water supply if a shallower supply is available. For these reasons, the groundwater-quality samples from aquifers in the Quaternary-, Tertiary-, and some Paleozoic-age hydrogeologic units most likely are 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.

5.5.1.4 Water quality characteristics

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the Snake/Salt 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 has a negative effect on crop production. High TDS concentrations also cause scale build-up in pipes and boilers. The USEPA has not set an MCL for TDS; however, the USEPA SMCL for TDS is 500 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 2012). 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 indicate that sodium is replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR is used in conjunction with information about the soil characteristics and irrigation practices in the area being examined. The high SAR of waters in some hydrogeologic units in the Snake/Salt River Basin indicates that these waters may not be suitable for irrigation.

Many groundwater-quality samples included in the dataset for this report contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA standards (U.S. Environmental Protection Agency, 2012) and WDEQ groundwater-quality standards (http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf).

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2012). The USEPA SMCL for sulfate is 250 mg/L, the WDEQ Class II groundwater (agricultural) standard is 200 mg/L, and the WDEQ Class III groundwater (livestock) standard is 3,000 mg/L.

Table 5-1. Selected groundwater quality standards and advisories.

[MCL, Maximum Contamination Level; AL, Action Level; SMCL, Secondary Maximum Contaminant Level; HAL, Lifetime Health Advisory Level; USEPA, U.S. Environmental Protection Agency; WDEQ, Wyoming Department of Environmental Quality; WQD, Water Quality Division: --, no data; N, nitrogen; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; SAR, sodium adsorption ratio; TDS, total dissolved solids]

Physical characteristics and constituents		Groundwater quality standards and advisories					
		Domestic[1]			Agricultural[2] Class II (WDEQ/WQD)	Livestock[2] Class III (WDEQ/WQD)	Industry[2] Class IV (WDEQ/WQD)
		MCL or AL (USEPA)	SMCL (USEPA)	HAL (USEPA)			
Physical characteristics	pH (standard units)	--	6.50–8.50	--	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	10,000
	SAR (ratio)	--	--	--	8	--	--
Trace elements (µg/L)	aluminum (Al)	--	50–200	--	5,000	5,000	--
	antimony (Sb)	6	--	--	--	--	--
	arsenic (As)	10	--	--	100	200	--
	barium (Ba)	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 unless otherwise noted)	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 U.S. Environmental Protection Agency 2012 edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2012).

[2]Selected from Wyoming Department of Environmental Quality Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters (Wyoming Department of Environmental Quality, 1993 [revised 2005], 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 picocuries per liter standard is a proposed Maximum Contaminant Level, whereas the 4,000 picocuries per liter standard is a proposed alternative Maximum Contaminant Level for communities with indoor air multimedia mitigation programs (U.S. Environmental Protection Agency, 1999).

High chloride concentrations can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops (U.S. Environmental Protection Agency, 2012; Bohn and others, 1985, and references therein). The EPA SMCL for chloride is 250 mg/L, the WDEQ Class II groundwater (agricultural) standard is 100 mg/L, and the WDEQ Class III groundwater (livestock) standard is 2,000 mg/L. 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, 2012). 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 (U.S. Environmental Protection Agency, 2012). The USEPA has established SMCLs of 300 micrograms per liter (µg/L) for iron and 50 µg/L for manganese. High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.5.1.5 Statistical analysis

In relation to groundwater quality, analysis has two meanings in this report, *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* (6 milligrams of calcium per liter of water). The chemical analysis may include physical measurements of chemical properties such as pH (a measure of hydrogen ion activity). The statistical analysis of a *set* of chemical analyses is the mathematical treatment of the dataset to describe and summarize those data in order to convey certain useful descriptive characteristics; for example, *the calcium concentration in groundwater samples from this hydrogeologic unit 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 used to assemble, analyze, and present water-quality data for samples of groundwater from the Snake/Salt River Basin. From these data, *summary statistics* were derived for physical properties and major-ion chemistry of groundwater in hydrogeologic units in the Snake/Salt River Basin, as tabulated in **appendices E-1** to **E-6** for environmental 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 (extracted from the ground) with oil and gas or water samples collected during exploration for oil and gas. The water-quality data for the hydrogeologic units in the Snake/Salt River Basin also are compared to USEPA and WDEQ standards for various water 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 of environmental water samples (**appendices E-1** through **E-6)**. Censored data are data reported as above or below some threshold, such as "below detection limit" or "less than (<) 1 mg/L." For very few major-ion samples, censored values ("less-than") were reported for a major-ion constituent. These censored values were treated as uncensored values at the laboratory reporting level, for statistical analysis. For uncensored datasets with a sample size of 1, only a minimum value is reported in **appendices E-1** through **E-6**; 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. Concentrations of nutrient, trace element, and radiochemical constituents were reported as uncensored values in environmental water datasets for some hydrogeologic units. For nutrient, trace element, and radiochemical datasets without censored values, the convention used for uncensored data was used to report summary statistics. Environmental water datasets for other hydrogeologic units contained censored values, including censored values that 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 are 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 dataset; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. In some cases, environmental water datasets for a constituent and hydrogeologic unit could not meet the minimum sample size or uncensored value requirements for the AMLE technique. In those cases, constituents within a hydrogeologic unit that had a sample size of 1, a minimum value (censored or uncensored) is reported, and for a sample size of 2 or greater, a minimum value (censored or uncensored) and maximum value are reported, or only a maximum censored value is reported. For a few constituents that did not have any censoring, standard summary statistics could be determined and are reported. In some cases, a dataset for a constituent and hydrogeologic unit was insufficient for determining complete summary statistics with the AMLE technique; however, individual samples could be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedances frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedances were calculated and reported as the number of samples with exceedances out of the total number of quality samples analyzed for that property or constituent for a hydrogeologic unit. When only one sample was available and exceeded a standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent.' Groundwater-quality standard exceedances frequencies were determined using the filtered analyses for a constituent because filtered analyses were more common (or frequently were the only analyses available). Only samples for a constituent that were analyzed at a laboratory 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 five samples were 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 could be compared to the SMCL of 50 µg/L for manganese. The sample with the value of <100 µg/L could not 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 two of four samples exceeded the SMCL of 50 µg/L. Complete summary statistics for manganese would not be included in the appendix for the hydrogeologic unit in this example because too many of the available values were censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the dataset was not met. For this example, only a maximum value of <100 µg/L would be reported in the appendix. Descriptions of the constituents that were included in the statistical summaries for environmental water samples are summarized in the next section.

5.5.1.5.1 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, the WRDS database, and other sources such as consulting engineers' reports related to water supply exploration and development. The physical properties and constituents presented in this report are pH, specific conductance, major ions, nutrients, trace elements, and radiochemicals.

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

Major-ion chemistry of environmental waters, comprising major ions and associated properties or constituents, was reported as laboratory analyses of filtered waters (or constituents were calculated from laboratory analyses). Major-ion chemistry constituents and related properties were hardness (calculated and reported as calcium carbonate), dissolved calcium, dissolved magnesium, dissolved sodium, dissolved potassium, SAR (calculated), alkalinity (reported as calcium carbonate), dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and TDS.

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) commonly was available and included in the dataset. 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 included in the dataset if available. 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 alkalinity value was used; and if that was not available, an unfiltered field value of ANC was used to report alkalinity. Some alkalinity values were computed from the bicarbonate reporting form to the calcium carbonate reporting form. These constituents are reported in milligrams per liter (mg/L).

Because there were many different types of laboratory analyses, including different analytical methods and different reporting forms (for example, concentrations reported as nitrate or as nitrogen), only a subset of the nutrient constituents were selected from the final datasets and used for calculation of summary statistics. Nutrient constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the summary statistics are dissolved ammonia (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved orthophosphate (reported as phosphorus), dissolved phosphorus (reported as phosphorus), and dissolved organic carbon. Total ammonia (reported as nitrogen), total ammonia plus organic nitrogen (reported as nitrogen), and total phosphorus (reported as phosphorus), analyzed in a laboratory using unfiltered water samples, were included in the summary statistics. In addition, total organic nitrogen and total nitrogen, computed using analyses of the individual constituents, were included in the summary statistics. Nutrient constituents are reported in milligrams per liter (mg/L).

Trace element constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were dissolved 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 datasets. These constituents are reported in micrograms per liter (µg/L). Radiochemical constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were gross alpha radioactivity, gross beta radioactivity, dissolved radium-226, dissolved radium-228, dissolved uranium (natural), and radon-222 (unfiltered) (referred to herein as "radon"). All radiochemical constituents are reported in picocuries per liter (pCi/L) except uranium, which is reported in micrograms per liter (µg/L).

5.5.1.5.2 Produced-water samples

Produced-water samples are from wells related to natural resource extraction (primarily oil and gas production). Chemical analyses for produced-water samples were compiled from the USGS PWD. Only two produced water samples from the USGS

PWD were located and are included in this report. The physical properties and constituents presented in this report for produced-water samples are pH, TDS, and major ions.

The physical properties and major ion chemistry for the two produced water samples included in this report generally were the same as for environmental waters, with some exceptions. In the produced-waters dataset, the water phase (filtered or unfiltered) was not reported with the data so the analyses may include a mix of dissolved and total concentrations. The physical properties and major-ion chemistry characteristics presented herein are pH (in standard units), calcium, magnesium, potassium, sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, fluoride, silica, sulfate, and total dissolved solids (TDS). The method for determining TDS concentrations was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter (mg/L).

5.5.1.6 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Snake/Salt River Basin study area are plotted on trilinear diagrams for those hydrogeologic units with samples from at least three springs or three wells (**appendices F-1** through **F-6**). 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 F-1** through **F-6**). 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).

5.6 Aquifer sensitivity and potential groundwater contaminant sources

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the Snake/Salt River Basin. It is axiomatic that protecting groundwater from contamination is much more attainable than remediation should the resource be impacted by 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 (EPA), Region 8, 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 of the *Wyoming Groundwater Vulnerability Assessment Handbook* (the *Handbook)* by the Spatial Data and Visualization Center (SDVC; 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. 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 maps from the 1992 SDVC study are used to evaluate the potential for groundwater contamination in the Snake/Salt River Basin: 1) a map of average annual recharge (**fig. 5-2**), and 2) a map of aquifer sensitivity (**fig. 5-3**). **Figures 5-4** through **5-10** map potential groundwater contaminant sources in the Snake/Salt River Basin. Additional discussion on the rationale for and methodology used in developing **figures 5-1** through **5-10** is provided in **appendix C**.

5.6.1 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 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 **(fig. 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 (Aller and others, 1985) based on six independent parameters:

- Depth to initial groundwater,
- Geohydrologic setting,
- Soil media,
- Aquifer recharge (average annual),
- Topography (slope), and
- 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 Snake/Salt 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 (43-56) are located primarily over alluvial deposits; adjacent to rivers, streams, and lakes; and in the highly fractured mountain 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 fractured mountain units 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 Snake/Salt River Basin. These areas generally have relatively thicker, well-drained, mature soils; rolling topography with minor relief (lower slopes); and 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 (18-25) 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, or due to very low average precipitation, or both.

5.6.2 Potential sources of groundwater contamination

Figures 5-4 through **5-10** illustrate potential groundwater contaminant sources in the Snake/Salt River Basin. These generally include industrial, retail, private, and public facilities that manufacture, process, use, store, sell, dispose, or otherwise handle substantial volumes of waste and other substances with physical and 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 aquifers and the outcrop/recharge areas of confined aquifers. **Figure 5-3** shows areas where migration to the water table is most likely.

Many human activities have the potential to contaminate underlying groundwater resources. Possible sources of contamination include the following broad economic sectors: farming and ranching; resource development such as mineral extraction and logging; construction; transportation; residential, industrial and commercial development; and recreational activities. This section examines the potential for contamination from various point sources, that is, sources of pollution that can be traced to single definable places.

The identification and mapping of facilities as potential sources of groundwater contamination ***does not*** imply that they are impacting groundwater resources. Generally, these facilities are strictly regulated by one or more regulatory agency 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:

- Known 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

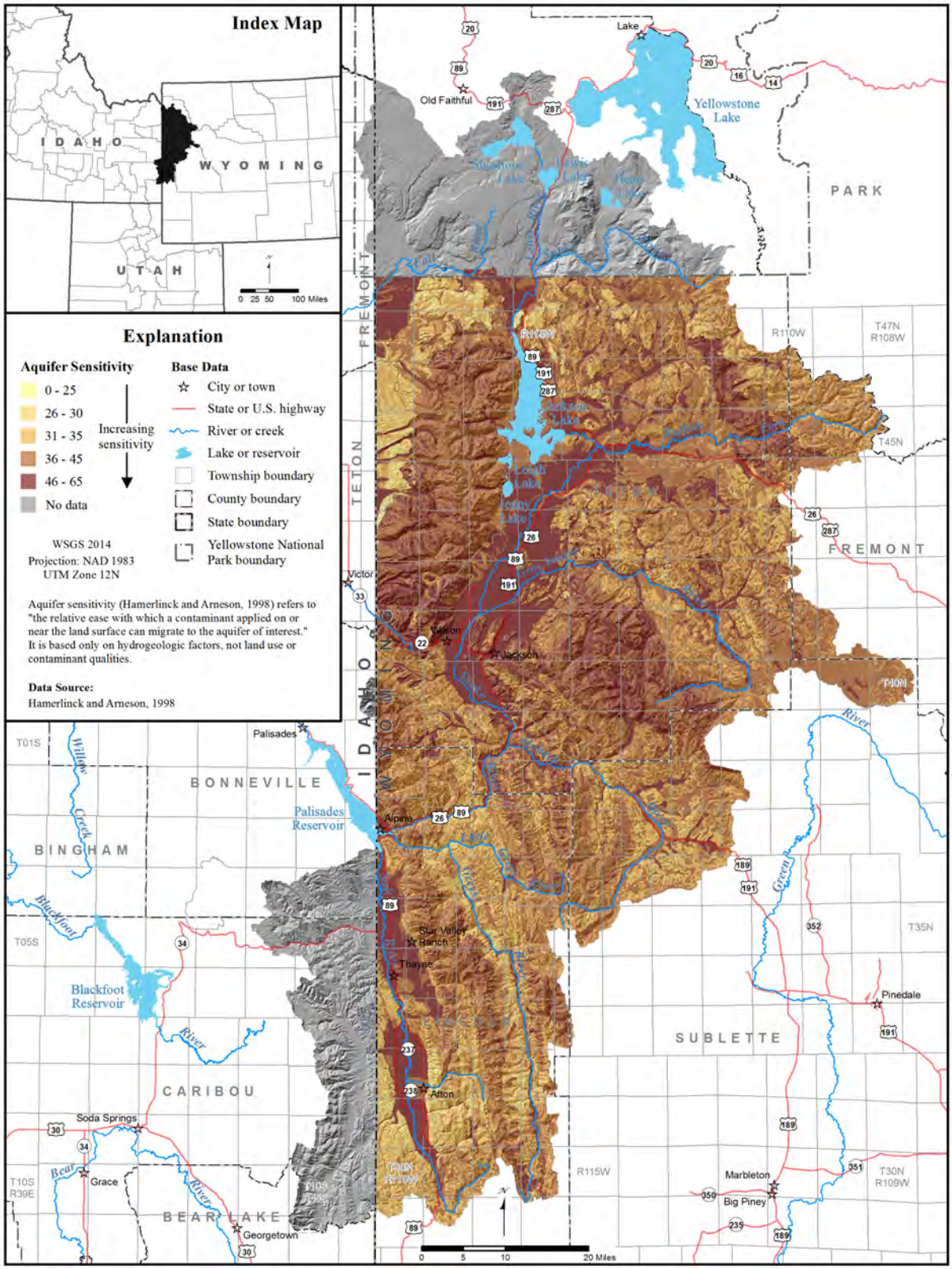


Figure 5-3. Aquifer sensitivity, Snake/Salt River Basin, Wyoming.

(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), and;
- Underground coal gasification sites.

WDEQ Solid and Hazardous Waste Division:
- Known contaminated sites regulated under the Voluntary Remediation Program (VRP), including orphan and brownfield assistance sites;
- Permitted disposal pits and other small treatment, storage, and disposal (TSD) facilities;
- Landfills, and;
- 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, and;
- Produced water pits.

Wyoming State Geological Survey:
- Oil and gas fields, plants, compressor stations;
- Pipelines;
- Mines (active and inactive), and;
- Gravel pits, quarries, etc.

These agencies 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 (**pl. 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

The sole petroleum infrastructure shown in **figure 5-4** is the Hoback Canyon gas delivery pipeline. Additional information about petroleum infrastructure can be obtained online from: http://wogcc.state.wy.us/.

- **Oil and gas fields:** WOGCC records indicate that oil and gas wells in the Snake/Salt River Basin were exploratory wells only, and they have all been plugged and abandoned. The three gas fields shown in **figure 5-4** (Sohare, Cabin and Game Hill) contained only wells that never produced significant quantities of oil, natural gas or produced water.

- **Pipelines:** Inter- 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, releasing substantial volumes of contaminants. The sole petroleum infrastructure shown in **figure 5-4** is the Hoback Canyon gas delivery pipeline.

- **Active and permanently abandoned injector and disposal wells:** Wells for disposal or for maintaining reservoir pressure in enhanced oil recovery, among other purposes, are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources. Class II wells, strictly regulated by the WOGCC and the BLM/EPA, 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. There are no WOGCC injection or disposal wells in the Snake/Salt River Basin.

Figure 5-5 – Potential groundwater contaminant sources: Class I and V injection wells in the WDEQ UIC 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 (Resource Conservation and Recovery Act (RCRA) definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal contributes a large component of injected fluids. Class I wells generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they accept for injection. In contrast, Class V facilities 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 three Class V facilities permitted to inject industrial 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 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 injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells inject fluids for in situ solution mining of various minerals (e.g., uranium, sulfur, copper, 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.

Figure 5-6 – Potential groundwater contaminant sources: WQD groundwater pollution control facilities, commercial oil pits, and active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program

- **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.

- **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 and sold prior to wastewater injection. Releases can occur from operational malfunctions, leaking from surface pits, and leaks from pipes and storage tanks.

- **Active and expired WYPDES outfalls:** Discharge of any potential pollutant from a point source into surface waters of the state requires a Wyoming Pollutant Discharge Elimination System (WYPDES) permit. During flow to surface waters where contaminant concentrations may be diluted, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits, and other impoundments are commonly installed along WYPDES flow paths to store

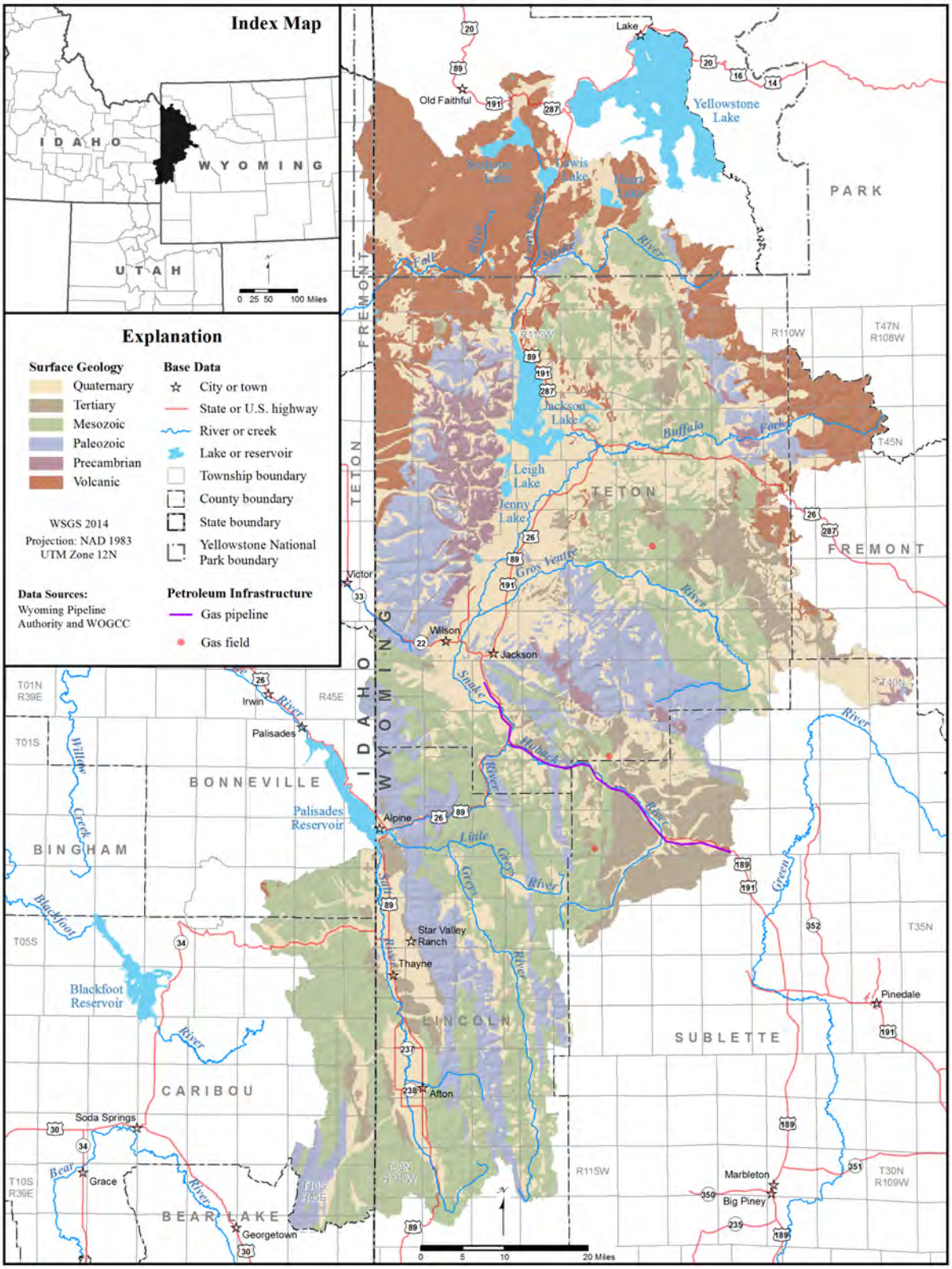


Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, gas processing plants, and Class II injection and disposal wells, Snake/Salt River Basin, Wyoming.

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 Snake/Salt River Basin.

Figures 5-7 through **5-9** 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 can hydraulically connect contaminants to the water table. Atmospheric exposure of metal-rich minerals can oxidize and mobilize through dissolution. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) more quickly infiltrates the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-7 – 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 5-8 – 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 WDEQ'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.

Figure 5-9 – 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 5-9** was compiled prior to and independently of the data compiled for **figures 5-7** and **5-8**, it might provide a more comprehensive picture of mining locations in the Snake/Salt River Basin.

Figure 5-10 - Volunteer Remediation Program (VRP) sites, storage tanks, 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, and;
- Illegal dump sites and historic site cleanups.

- **VRP 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).

- **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.

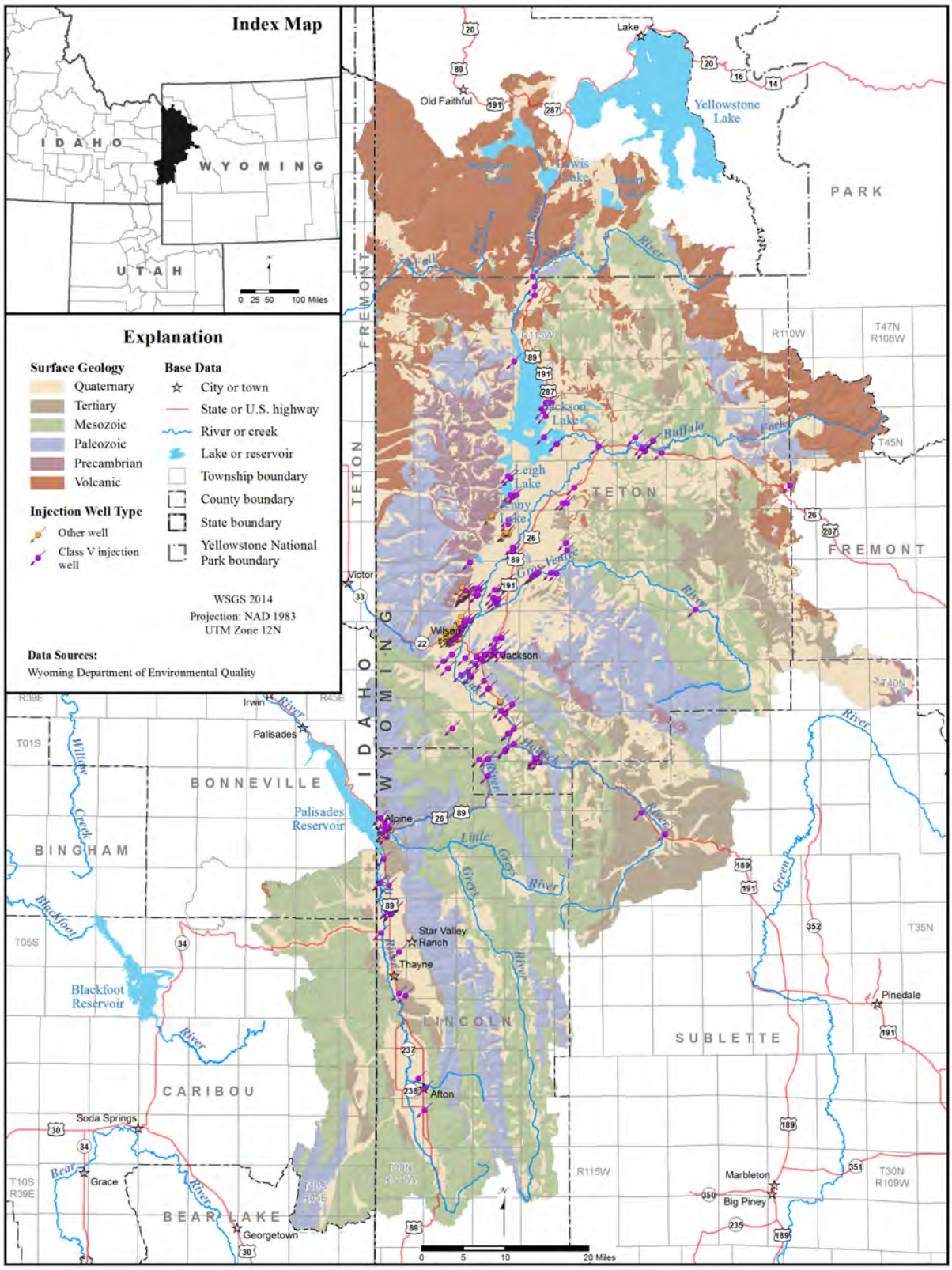


Figure 5-5. Potential groundwater contaminant sources: Class I and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, Snake/Salt River Basin, Wyoming.

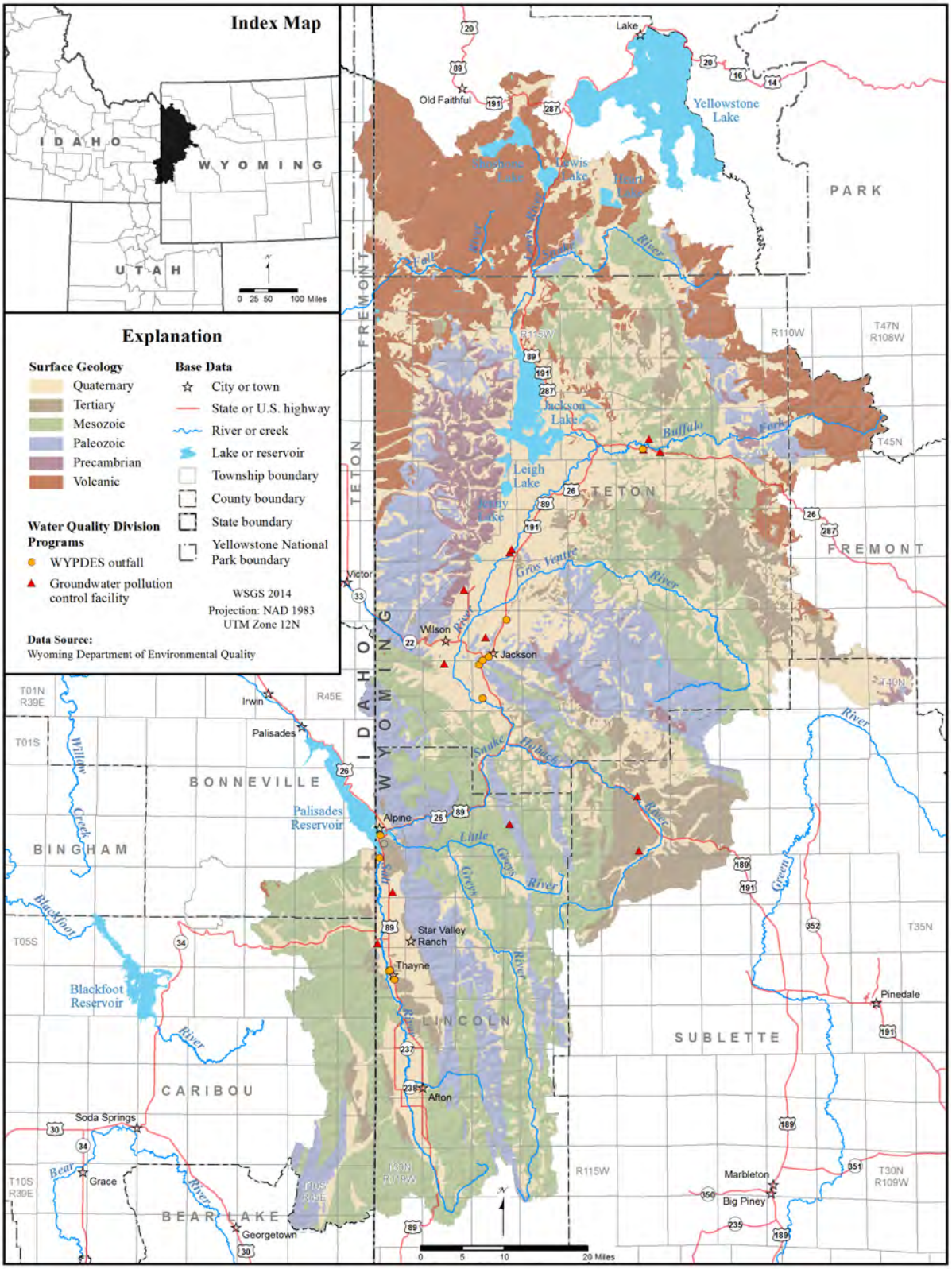


Figure 5-6. Potential groundwater contaminant sources: Active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program and WDEQ groundwater pollution control facilities, Snake/Salt River Basin, Wyoming.

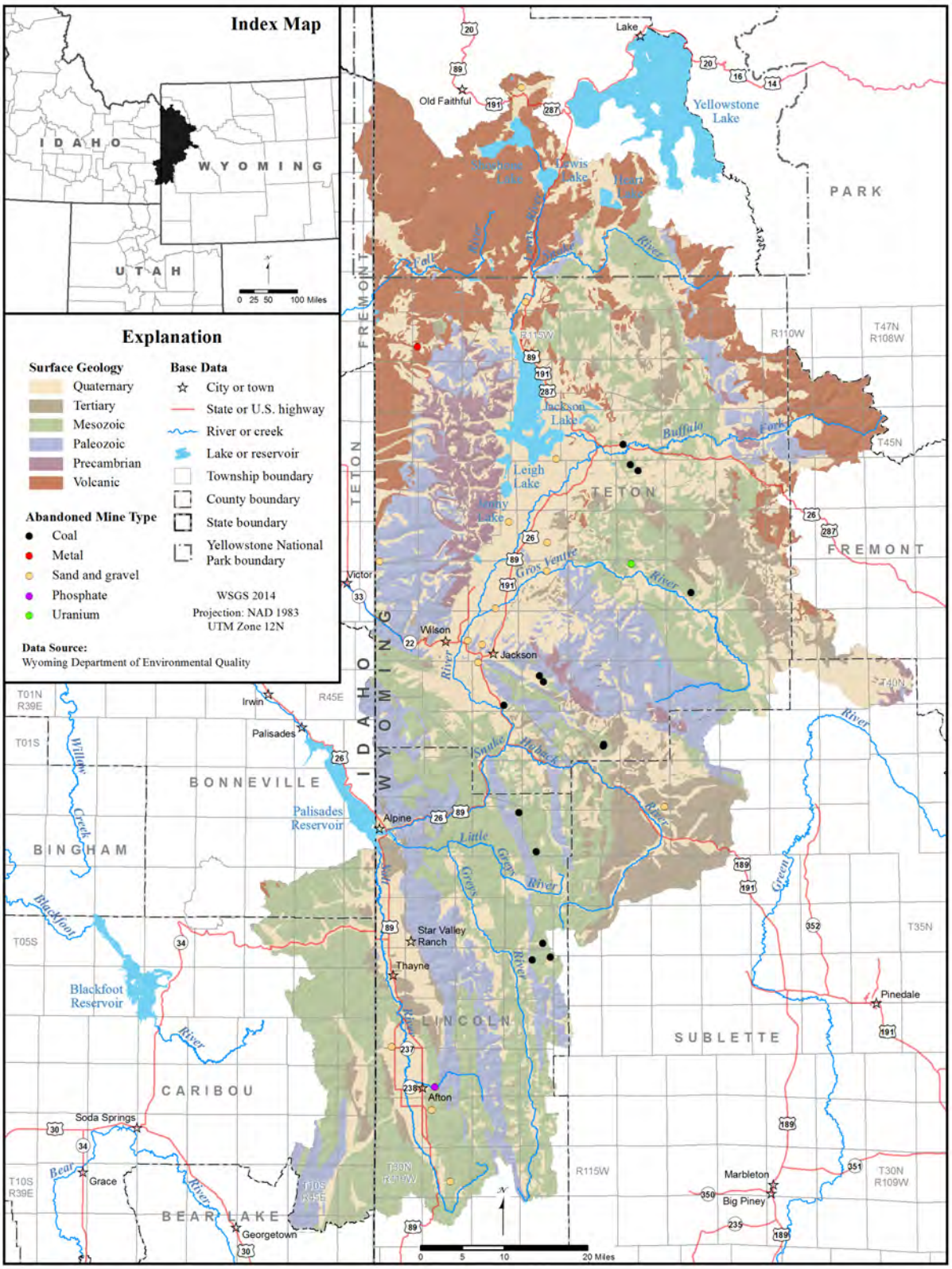


Figure 5-7. Potential groundwater contaminant sources: WDEQ Abandoned Mine Land Division abandoned mine sites, Snake/Salt River Basin, Wyoming.

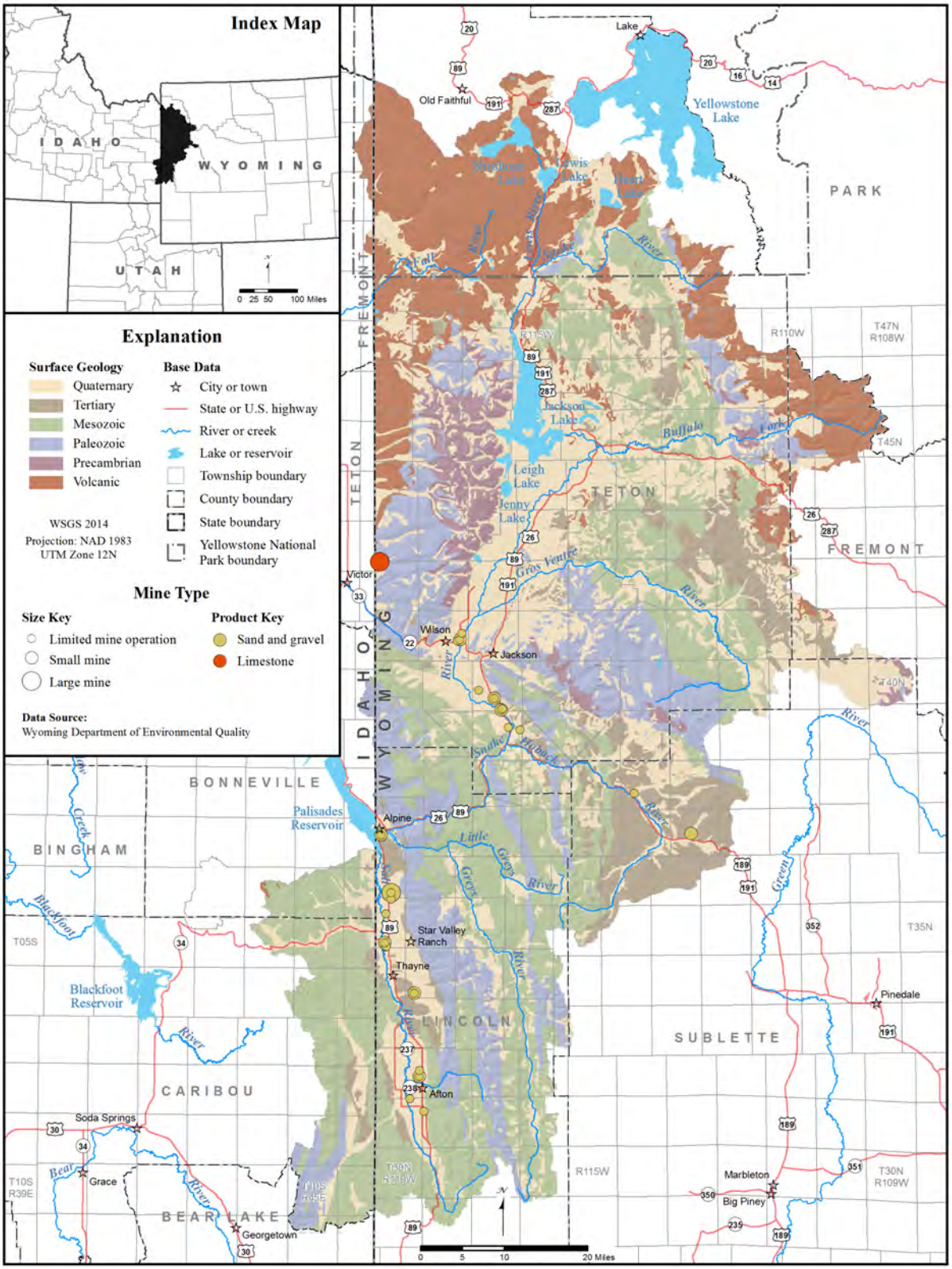


Figure 5-8. Potential groundwater contaminant sources: WDEQ Land Quality Division permitted mines, quarries and pits, Snake/Salt River Basin, Wyoming.

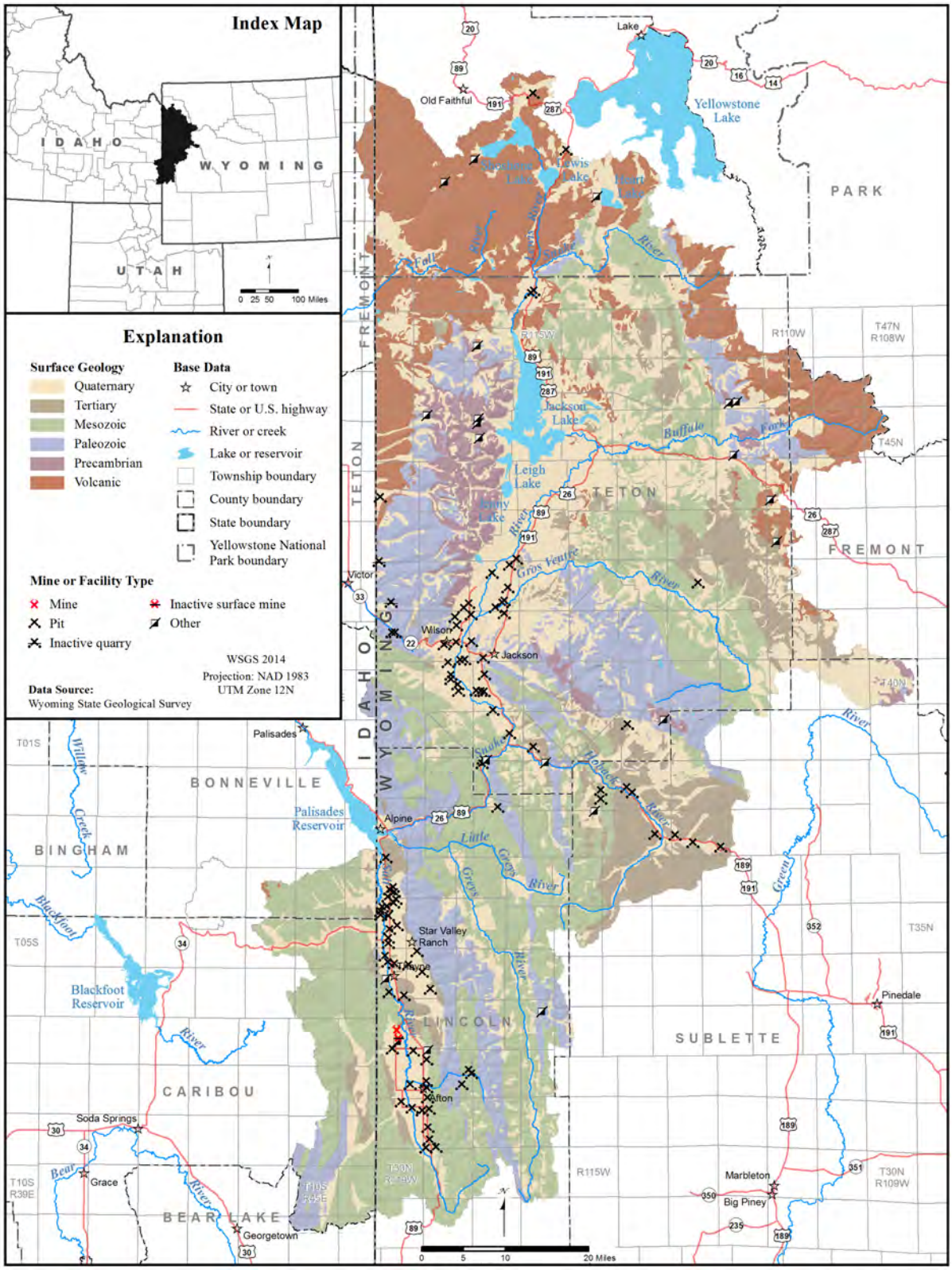


Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Snake/Salt River Basin, Wyoming, (locations from Harris, 2004).

- **Solid and hazardous waste facilities:** These contain a great number of potential contaminants in a variety of configurations. Wastes may be liquid, solid, or semisolid and stored either 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 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.

5.6.3 Discussion

To be included in this study, location data for potential contaminant sources had to be in formats that could be imported into ArcGIS databases. Some contaminant source types do not currently have the location data in the ArcGIS format required for mapping, or the data exist but were unavailable. The following types of potential groundwater contaminant sources were not mapped in this study:

- Although a number of public owned treatment works (POTWs) and septic systems exist in the Snake/Salt 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 (**fig. 5-5**).

- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the 2003 Snake/Salt River Basin Final Report (Sunrise Engineering, 2003) shows the primary areas where agricultural chemicals would generally be applied in the Snake/Salt River Basin. In addition, recent USGS reports (Bartos and others, 2009; Eddy-Miller and Norris 2000; Eddy-Miller and Remley, 2004; Eddy-Miller and others, 2013) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC report (Hamerlinck and Arneson, 1998) 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 (UCG) sites in the Snake/Salt River Basin.

- There are no WOGCC water pits, gas plants or compressor stations in the Snake/Salt River Basin.

- 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 SHWD but are not shown on **fig. 5-10** 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 Snake/Salt River Basin groundwater technical memorandum.

5.6.4 Source Water Assessment, Wyoming Water Quality Monitoring, and associated groundwater protection programs

The federal government, under the Clean Water Act, recognized that states have primary responsibility for implementing programs to

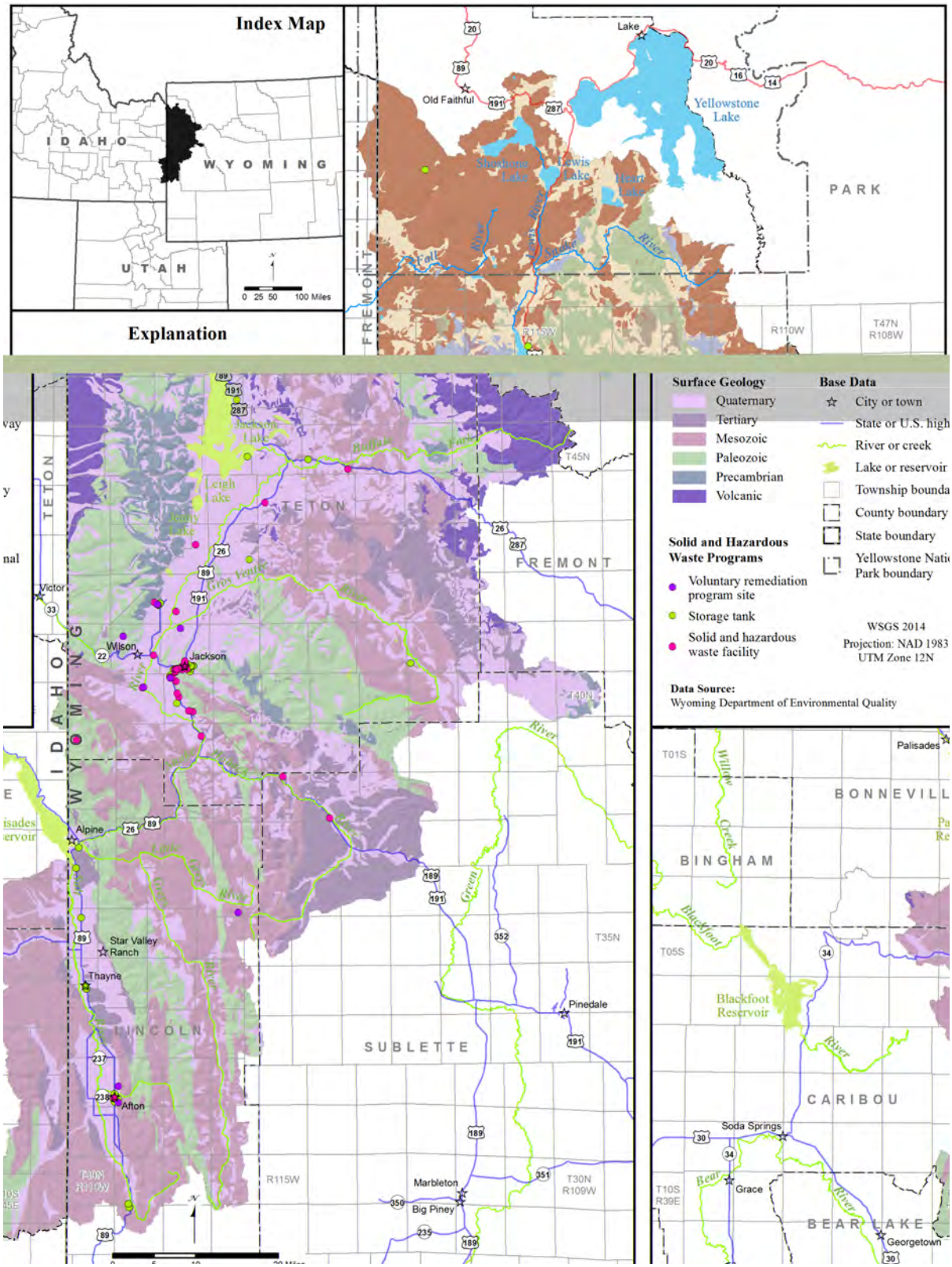


Figure 5-10. Potential groundwater contaminant sources: WDEQ permitted storage tanks, Voluntary Remediation Program (VRP), and permitted solid and hazardous waste facilities, Snake/Salt River Basin, Wyoming.

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; and
- The USGS Pesticide Monitoring Program in Wyoming.

A general discussion of these programs follows. More information can be obtained from the 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 **(fig. 5-11)**.

Additional information on the SWAP in Wyoming can be accessed at: http://deq.state.wy.us/wqd/www/.

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)
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

Phases III and IV of the program are currently being conducted.

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, presenting 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/index.asp. 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 artificial 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://water.usgs.gov/data/;
- 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, EPA, WWDO, WSGS, and SEO. 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 other 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 dataset 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.er.usgs.gov/publication/fs03300, http://pubs.er.usgs.gov/publication/fs20043093, http://pubs.usgs.gov/sir/2009/5024/, http://pubs.usgs.gov/fs/2009/3006/, 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

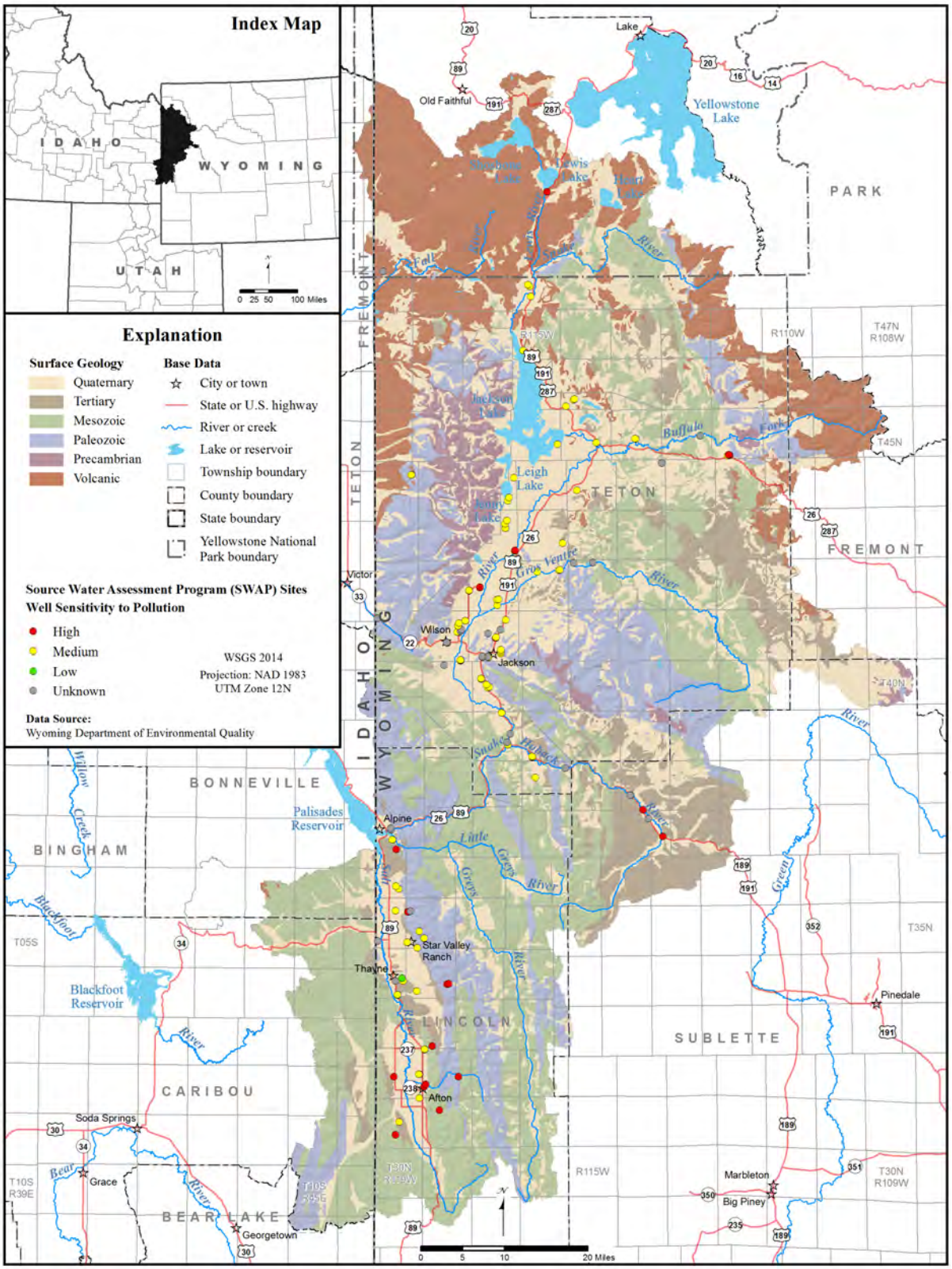


Figure 5-11. Surface Water Assessment and Protection, Snake/Salt River Basin, Wyoming.

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 are intended 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

Snake-Salt River Basin hydrogeology and groundwater resources

Karl Taboga and Paul Taucher

Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In terms of frequency of use, the primary hydrogeologic unit in the Snake/Salt River Basin is the Quaternary Snake/Salt River alluvium (Sunrise Engineering and others, 2003) (**figs. 8-1** through **8-7** and **pls. 4** through **6**). Additionally, over thirty five bedrock aquifers, ranging in geologic age from Paleozoic to Quaternary (**pls**. **2, 4, 5,** and **6**), exhibit heterogeneous permeability and provide variable amounts of useable groundwater.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (**section 5.1.1**). 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 Snake/Salt River Basin, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Phosphoria Formation is classified as both an aquifer and a confining unit in the Snake/Salt River Basin, and several springs discharge water from this formation at the surface (**pl. 3**). Permeability can vary widely within an individual geologic unit depending on its lithology and the geologic structure present. Carbonate aquifers, such as the Madison Limestone, commonly exhibit the highest yields in areas where secondary permeability (e.g., solution openings, bedding plane partings, and fractures) has developed. The great differences in permeability between and within geologic units account, in part, for the observed variation in the available quantity and the quality of a basin's groundwater resources.

One of the primary purposes of this study is to evaluate the groundwater resource of the Snake/Salt River Basin primarily through the following tasks (**chapter 1**):

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

Although an enormous quantity of groundwater is stored in the Snake/Salt River groundwater basin, the basin's complex geology (**chapter 4**) does not permit the use of the general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties. Hydrogeologists commonly employ these assumptions 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 evaluated in this study rely on previous estimates (Hamerlinck and Arneson, 1998) of the percentage of precipitation in areas where aquifer units outcrop that will ultimately reach the subsurface as recharge (**figs**. **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**.

Similarly, the extensive hydrogeologic data required to estimate the safe yield of groundwater for the entirety of the Snake/Salt River Basin does not exist. Furthermore, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915), and many scientists and water managers have largely abandoned this principle in favor of concepts such as sustainable development. The recharge volumes estimated in this chapter provide a first step to evaluating sustained yields for the basin's hydrologic units. The historical development of the safe yield concept and its technical context is discussed in **section 5.1.4**.

6.1 Hydrostratigraphy and recharge to aquifer outcrop areas

To begin the process of evaluating recharge, specific aquifers and groups of aquifers to which the recharge calculations will be applied must be distinguished (**figs**. **6-1** through **6-6**). Several previous studies (**section 2.1**) have grouped the Snake/Salt River Basin's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units. The hydro-

stratigraphy developed for this study is based on previous regional assessments and is summarized in the hydrogeology map illustrated in **plate 2** in the hydrostratigraphic charts shown on **plates 4** through **6** and in **chapter 7**. The hydrostratigraphic charts in **plates 4, 5, 6** detail the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering and others, 2007). **Appendix A** describes 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 (USGS) and Wyoming State Geological Survey (WSGS), were used to develop **plate 2**. Love and Christiansen (1985), however, were not able to distinguish all stratigraphic units present in the Snake/Salt River Basin due to the sheer size of the dataset and cartographic limitations. Therefore, some geologic units were not mapped individually but instead, are shown on **plate 2** as undifferentiated hydrogeologic units. To address this deficit, the outcrops of hydrogeologic units that were assigned as aquifers or aquifer groups in **plate 2** are aggregated by geologic age. These aggregated aquifers, or aquifer recharge zones, were generated as GIS shapefiles and used to calculate recharge volumes and rates:

- Quaternary aquifers (**fig. 6-1**)
- Tertiary aquifers (**fig. 6-2**)
- Mesozoic aquifers (**fig. 6-3**)
- Paleozoic aquifers (**fig. 6-4**)
- Precambrian aquifers (**fig. 6-5**)
- Volcanic aquifers (**fig. 6-6**)

6.2 Average annual recharge

Only a fraction of the groundwater stored in the Snake/Salt River Basin can be withdrawn for beneficial use because groundwater naturally discharges to streams, springs, lakes, and wetlands and is further lost through evapotranspiration. Under natural conditions, a state of dynamic equilibrium in which natural discharges to surface waters and evapotranspiration are counterbalanced by recharge exists. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge over time. Withdrawals from wells and springs remove groundwater from aquifer storage and natural discharges. Thus, without careful management, flows in springs, streams, and wetlands, as well as aquifer storage, will be depleted to such a degree that water rights holders will not receive their full appropriation and riparian ecosystems will collapse. This risk has long been recognized by Wyoming's agricultural community, as well as water managers for municipalities and conservation districts, state water administrators, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and also forms one of the core tenets in forming some of Wyoming's interstate water compacts, such as the Amended Bear River Compact of 1978 and 2001 Modified North Platte River Decree.

To evaluate recharge on a regional scale, this study combines estimated, average annual recharge data from the Spatial Data and Visualization Center (SDVC) (Hamerlinck and Arneson, 1998) and WSGS maps illustrating where pertinent hydrogeologic units outcrop in the Snake/Salt River Basin (**pl. 2**; **figs. 6-1** through **6-6**).

Average annual recharge constrained by best estimates of annual discharge (both natural and by pumping) and periodic water level monitoring provide valuable baseline data. These data assist in establishing benchmarks for sustained yield, namely the volume of water that can be artificially discharged without unacceptably depleting aquifer storage or natural discharges. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to constrain. Estimates of annual groundwater withdrawals and consumptive uses from the previous Snake/Salt River Basin water plans (Sunrise Engineering, 2003; WWDO, 2012) and the Statewide Framework Water Plan (WWC Engineering and others, 2007) are discussed in **chapter 8**.

Estimated, average annual, recharge (**fig. 5-2**) in the Wyoming portion of the Snake/Salt River

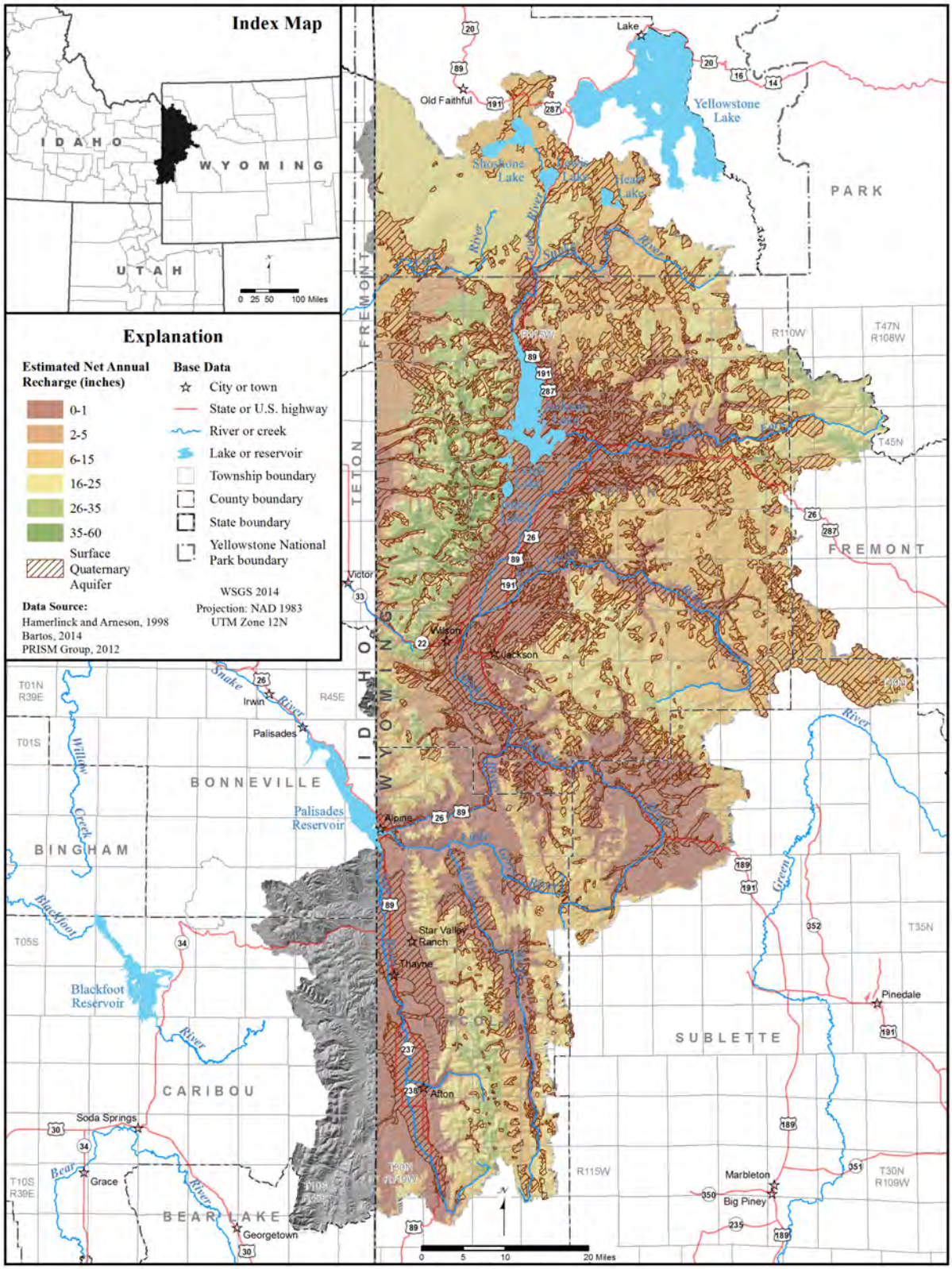


Figure 6-1. Estimated net annual aquifer recharge – surface Quaternary aquifer, Snake/Salt River Basin, Wyoming.

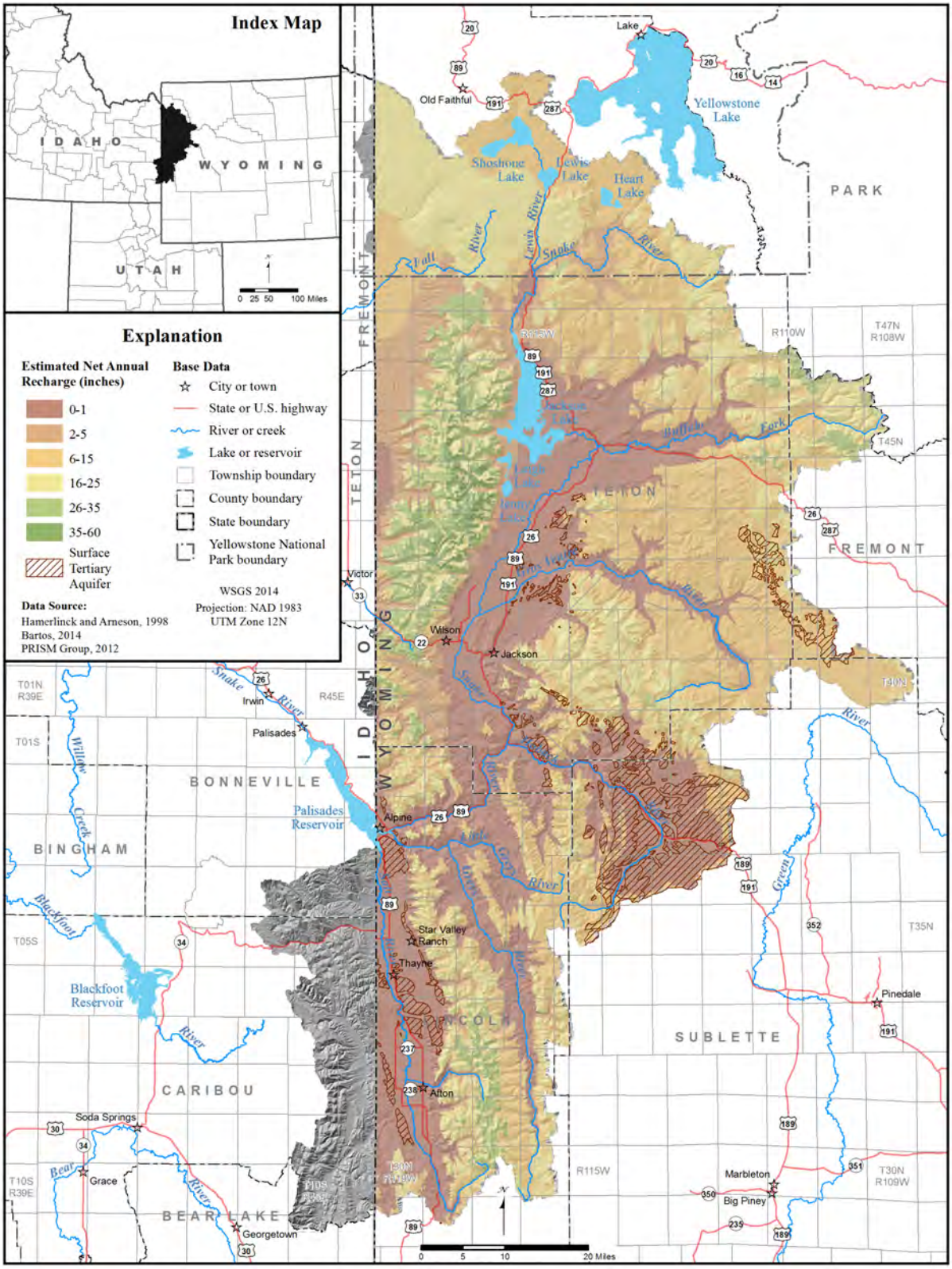


Figure 6-2. Estimated net annual aquifer recharge – surface Tertiary aquifer, Snake/Salt River Basin, Wyoming.

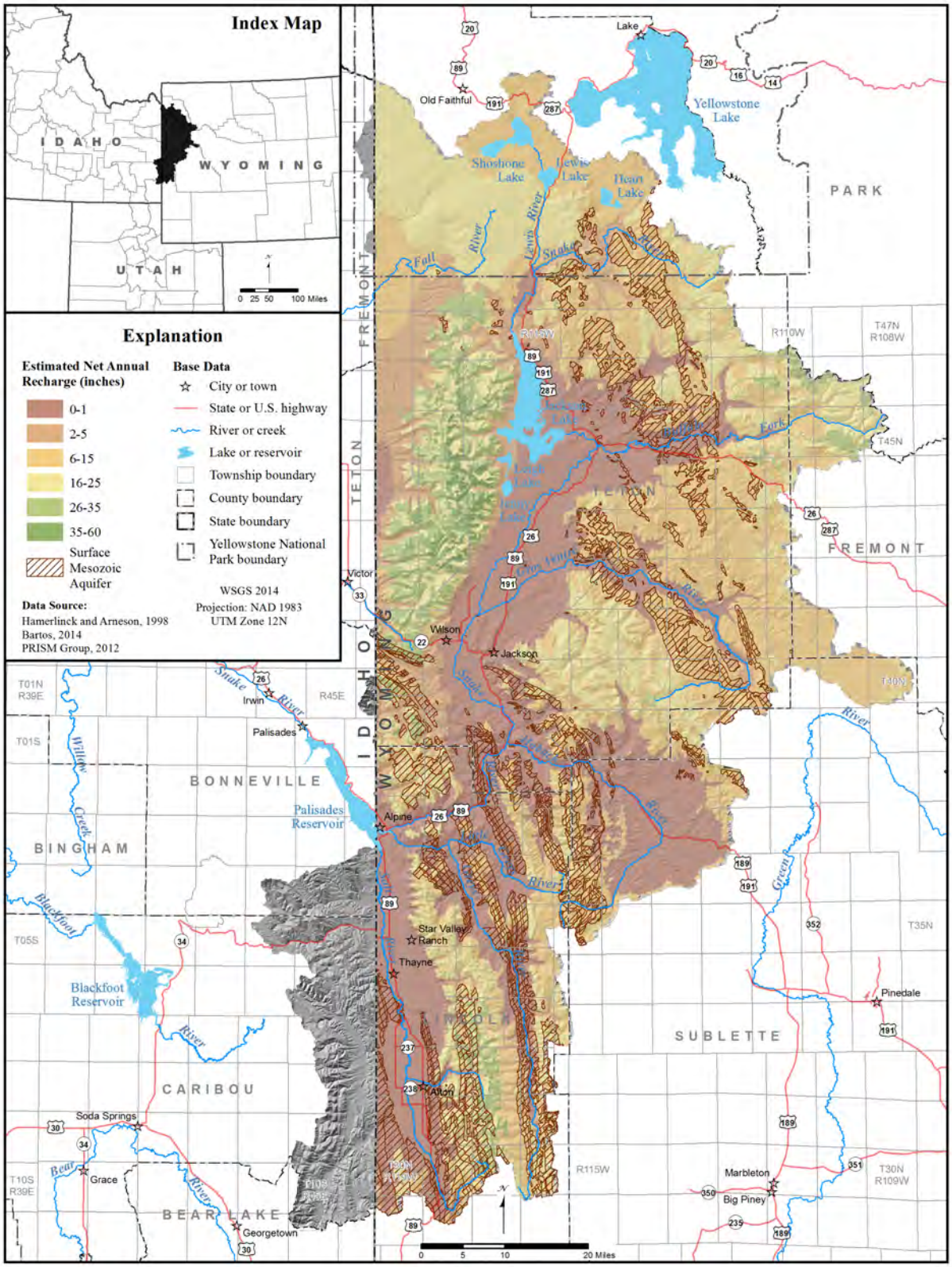


Figure 6-3. Estimated net annual aquifer recharge – surface Mesozoic aquifer, Snake/Salt River Basin, Wyoming.

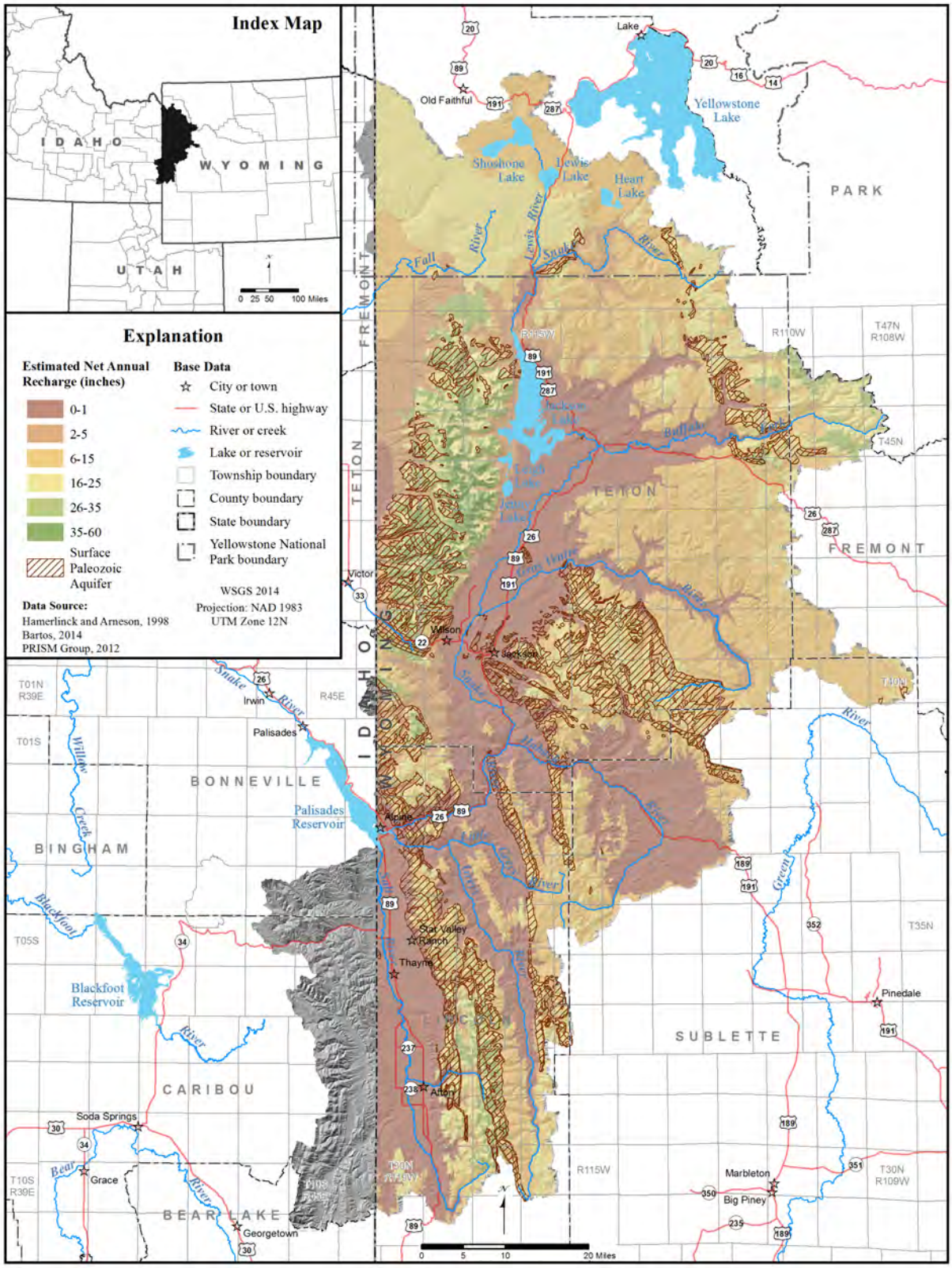


Figure 6-4. Estimated net annual aquifer recharge – surface Paleozoic aquifer, Snake/Salt River Basin, Wyoming.

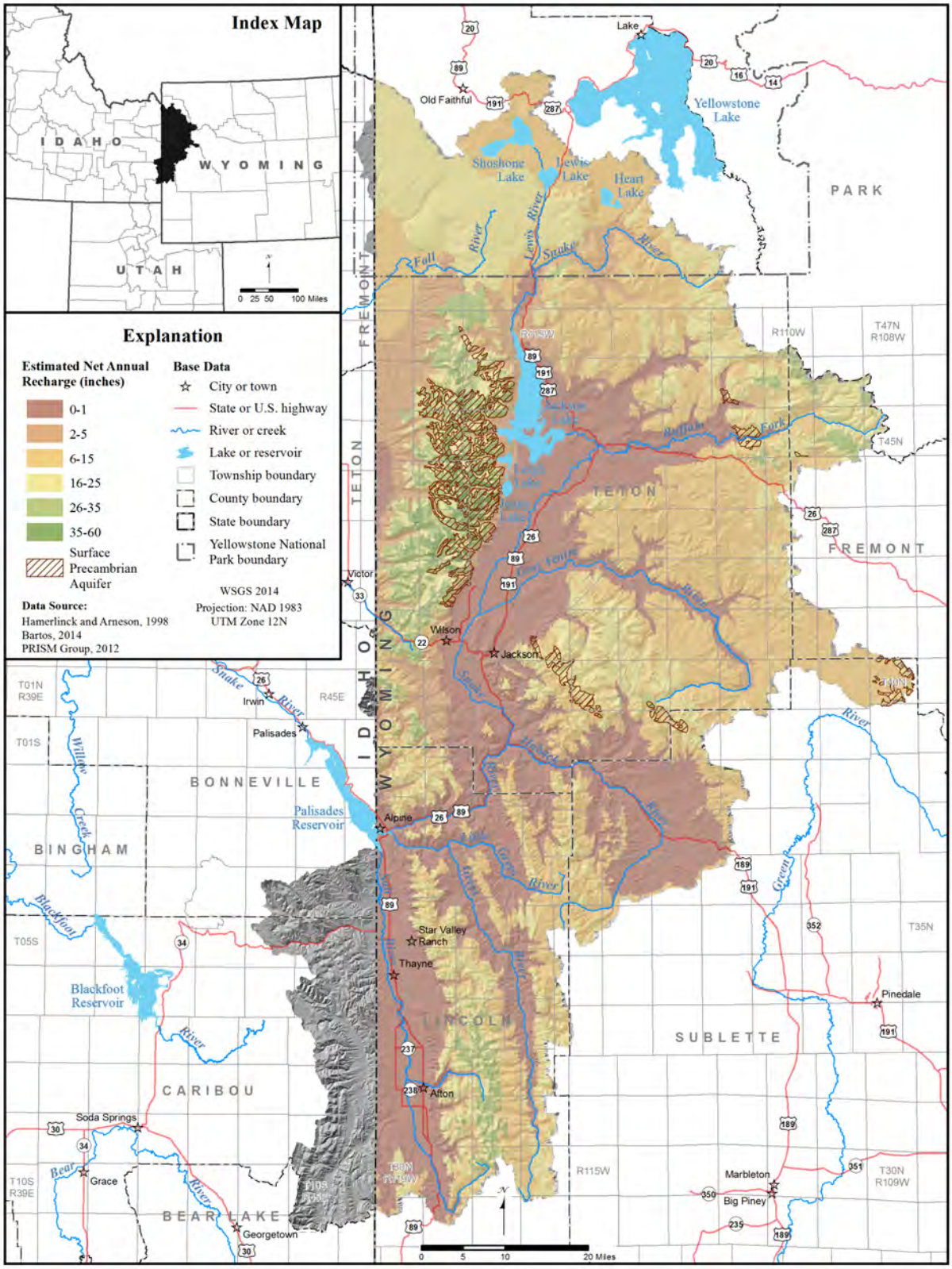


Figure 6-5. Estimated net annual aquifer recharge – surface Precambrian aquifer, Snake/Salt River Basin, Wyoming.

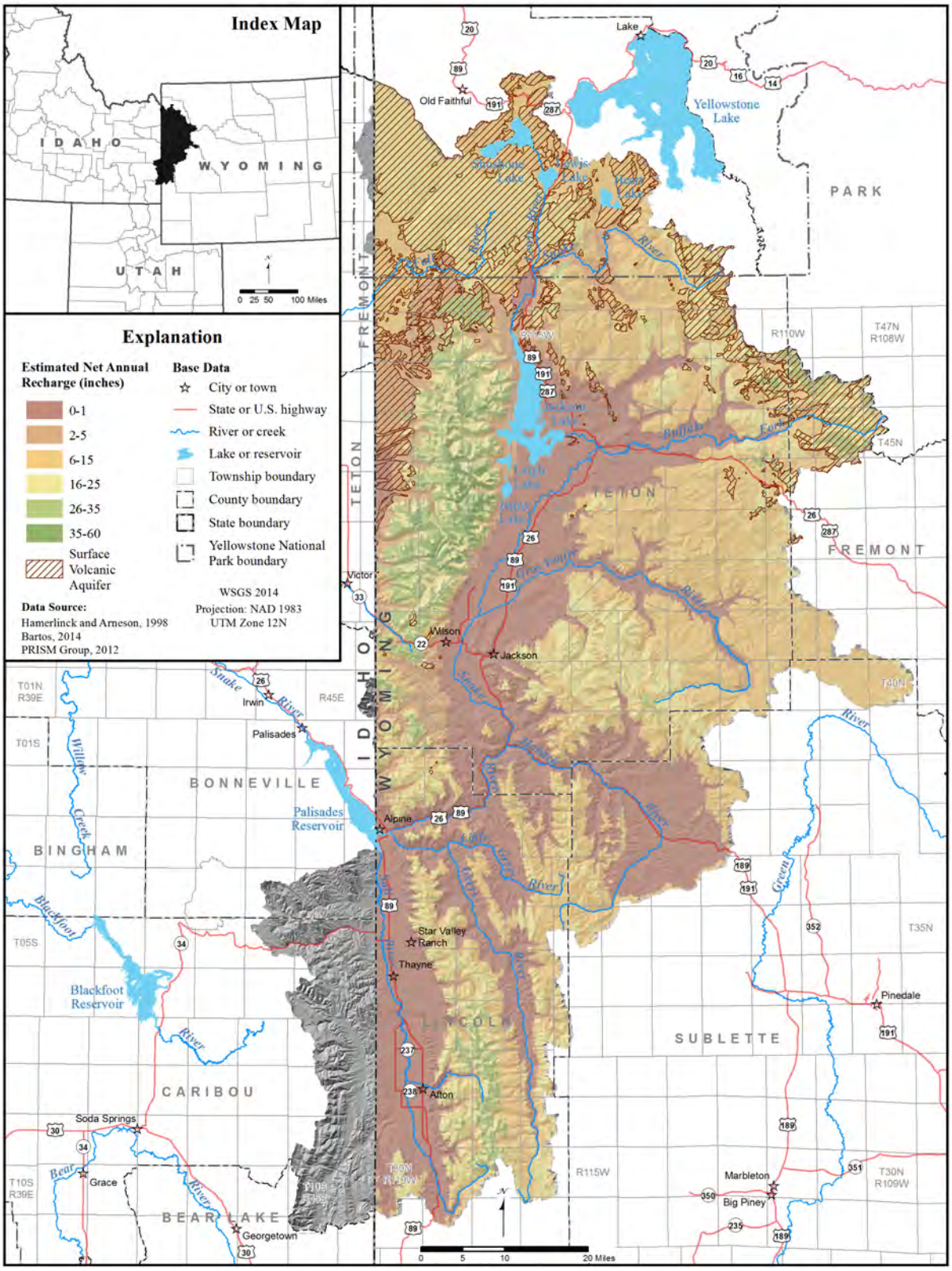


Figure 6-6. Estimated net annual aquifer recharge – surface Volcanic aquifer, Snake/Salt River Basin, Wyoming.

Basin ranges from less than one inch per year in the basin interior to over 35 inches per year in the surrounding mountains (Hamerlinck and Arneson, 1998). Mountains and foothills receive more recharge than basin lowlands due to environmental attributes characteristic of highland zones:

- Greater amounts of precipitation and more persistent snow pack (**fig**. **3-3**),
- More abundant vegetation,
- Soil and vegetation combinations more favorable to infiltration,
- Lower rates of evapotranspiration,
- Better exposure of the upturned and weathered edges of hydrogeologic units facilitates infiltration because zones of higher permeability often parallel bedding, and
- The presence of structural features that enhance recharge (e.g., faults, fractures, joints, and 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 Wyoming portion of the Snake/Salt River Basin and suggests what environmental factors exert control on recharge. Recharge is most efficient in the mountains of the Teton, Absaroka, Gros Ventre, Salt River, Snake River, and Wyoming ranges and are also slightly higher on the Yellowstone Plateau. The dataset for **figure 6-7** was generated by dividing 4,000-meter grid cells and assigning values for average annual, aquifer recharge (**fig**. **5-1**) and average annual precipitation (**fig**. **3-3**) to each cell; both data sets were obtained from the SDVC aquifer vulnerability study prepared for the State of Wyoming (Hamerlinck and Arneson, 1998).

Average annual recharge (**fig**. **5-2**) is based on percolation percentages for different soil/vegetation combinations multiplied by average annual precipitation for the 30-year period from 1981 to 2010. Total average annual precipitation has been estimated (PRISM, 2013) as 9,852,837 acre-feet for the larger Snake/Salt River Basin shown in **figure 3-3** and 9,137,284 acre-feet for the Wyoming portion exclusively (**table 8-2a**). Although this approach does not fully consider all factors that affect recharge, initial infiltration and precipitation levels are probably the most important factors on a regional scale. 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**. However, 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). Lastly, Hamerlinck and Arneson (1998) indicated that some areas in the basin interior receive zero amounts of recharge (**fig. 5-2**).

Table 6-1 shows the percentage of surface area by specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the six, age-classified, aquifer recharge zones (**pl. 2*;* figs. 6-1** through **6-6***)*.

Table 6-1 shows that most Quaternary and Tertiary aquifers receive recharge at efficiencies of six percent or less of precipitation. In contrast, most Mesozoic, Paleozoic, Precambrian and volcanic aquifers receive recharge at efficiencies greater than six percent, likely due to the fact that these aquifers are fractured and are exposed in upland areas. The consistently low recharge efficiencies calculated for Tertiary and Quaternary aquifer zones may reflect the subdued relief and greater aridity (**fig. 3-3**) within the interior of the Snake/Salt River Basin.

Recharge volumes for the established aquifer recharge areas were calculated with the following, general equation:

Average annual recharge volume (acre-feet) = Aquifer recharge area (acres) × Average annual recharge *(f eet)*

The outcrop areas assigned to aquifer groups in the recharge calculations **(figs**. **6-1** through **6-6)** were determined from the hydrogeologic map (**pl**. **2**) developed for this study. Average annual rates of recharge throughout the Snake/Salt River Basin (mapped in 100-meter cells) adapted from the Wyoming Groundwater Vulnerability Assessment

Table 6-1. Percent of aquifer recharge zones recharging at varying efficiencies.

Recharge Efficiency as annual recharge / annual precipitation, (in percent)	0-1%	2%	5%	6%	30%	35%	36%	40%	60%
Quaternary	2.72%	0.00%	1.22%	55.86%	0.00%	28.05%	5.14%	1.41%	5.60%
Tertiary	23.11%	22.69%	1.93%	23.77%	0.00%	24.96%	-	-	3.55%
Mesozoic	0.43%	0.00%	0.00%	38.37%	28.43%	12.04%	0.20%	0.13%	20.40%
Paleozoic	0.00%	-	-	22.13%	0.00%	22.42%	0.04%	0.21%	55.21%
Precambrian	-	-	-	8.87%	-	29.06%	-	-	62.07%
Volcanic	-	-	-	15.28%	0.00%	6.52%	5.19%	49.10%	23.91%

Handbook (Hamerlinck and Arneson, 1998) are shown in **figure 5-2**. Recharge rates were grouped into the five ranges to make **figure 6-7** 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.

Recharge calculations contained in this report do not incorporate confining unit outcrop areas (**pl. 2**). As noted in **section 5.2**, undifferentiated geologic units were included in the established aquifer recharge areas of the same age. Recharge calculations that exclude confining-unit outcrop areas provide a more conservative estimate of available groundwater resources. Furthermore, leakage from adjacent confining layers was also disregarded in this evaluation.

Table 6-2 summarizes calculated recharge for the Snake/Salt River Basin over the ranges of average annual recharge mapped on **figure 5-2** and the aquifer recharge zones displayed in **figures 6-1** through **6-6**. A "best total" amount for each range of recharge over the outcrop area of each aquifer group is provided in **tables 6-2** and **6-3** based on the recharge area for each whole inch of recharge in the database compiled for this study. The "best total" is calculated directly from the detailed cell-by-cell recharge data and the corresponding surface area.

Table 6-3 summarizes calculated, average annual recharge statistics from the more detailed calculations provided in **table 6-2**. Additionally, **table 6-3** provides a "best total," average recharge depth, delivered over the entire surface area of each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Precambrian aquifers receive 2.141 feet (25.7 inches) of recharge compared to about 6.5 and 3.1 inches, respectively, in Quaternary and Tertiary aquifers. The Mesozoic aquifers, which crop out in highland areas located primarily in northern and central parts of the basin (**pl. 2**), receive 0.77 feet (~9.2 inches) of recharge. Infiltration through Paleozoic and volcanic strata provides about 53% of the basin's recharge.

In the Wyoming part of the Snake/Salt River Basin, the best estimate of total recharge is 2,620,738 acre- feet, or 29 percent, of total precipitation.

6.3 Summary

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the Snake/Salt River Basin (**fig. 3-2**) has been estimated as 9,852,837 acre-feet and 9,137,284 acre-

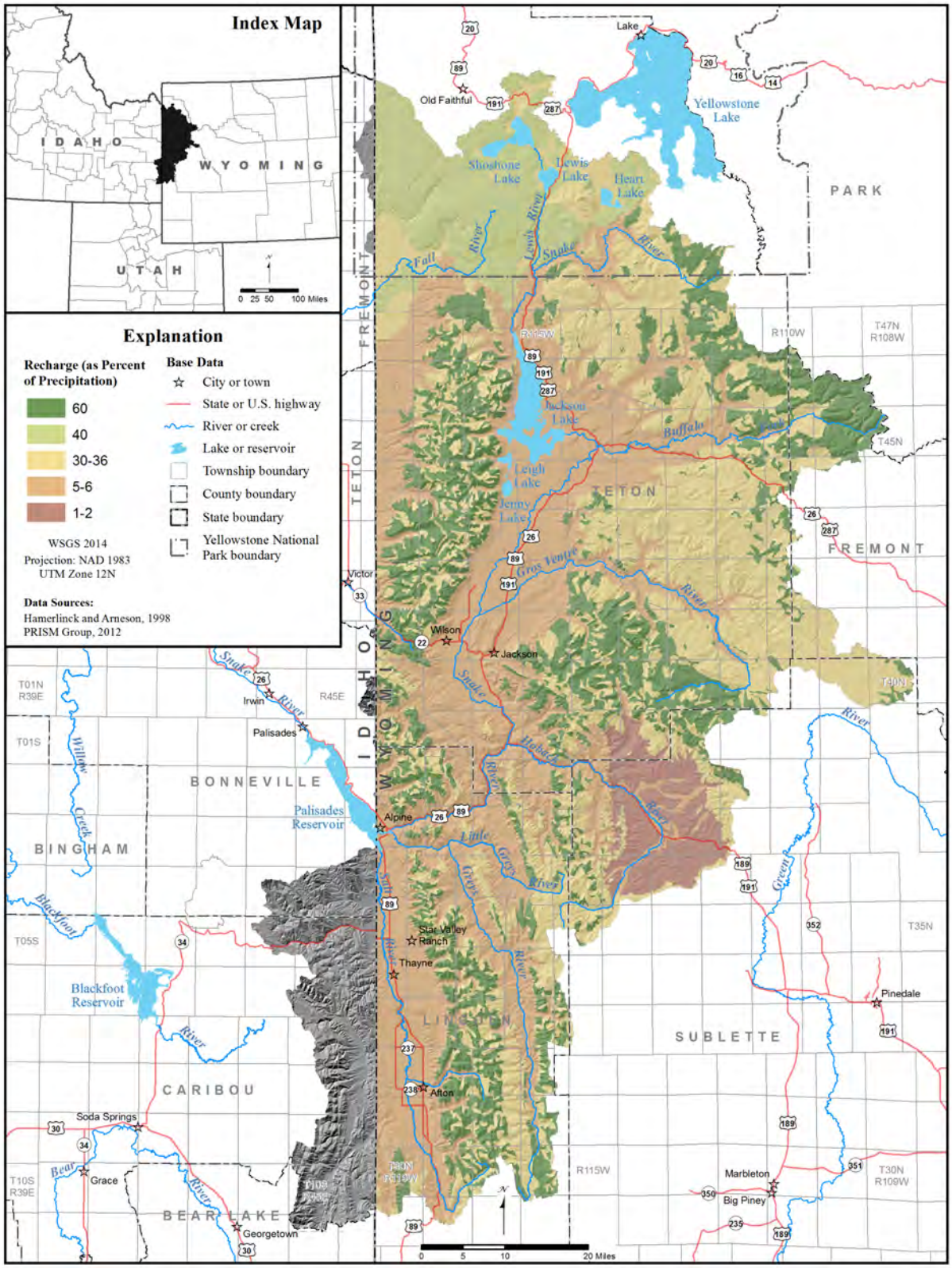


Figure 6-7. Aquifer recharge as percentage of precipitation using 1981 - 2010 precipitation normals, Snake/Salt River Basin, Wyoming.

Table 6-2. Snake/Salt River Basin average annual recharge calculations.

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (Acre-feet)
Quaternary	0	0.00	354,454	27,212
	1	0.08		
	2	0.17	257,699	44,483
	5	0.42		
	6	0.50	312,577	301,593
	15	1.25		
	16	1.33	72,100	116,362
	25	2.08		
	26	2.17	15,819.76	39,827.59
	35	2.92		
	35	2.92	5,503.25	18,532.01
	60	5.00		
	TOTAL		**1,018,153**	**548,010**

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Mesozoic	0	0.00	89,014	7,218
	1	0.08		
	2	0.17	126,424	21,664
	5	0.42		
	6	0.50	229,972	204,653
	15	1.25		
	16	1.33	76,859	130,242
	25	2.08		
	26	2.17	23,925	54,894
	35	2.92		
	35	2.92	0	0
	60	5.00		
	TOTAL		**546,194**	**418,671**

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Precambrian	0	0.00	45	4
	1	0.08		
	2	0.17	9,015	1,849
	5	0.42		
	6	0.50	5,802	6,046
	15	1.25		
	16	1.33	35,977	61,237
	25	2.08		
	26	2.17	30,694	81,116
	35	2.92		
	35	2.92	19,617	66,317
	60	5.00		
	TOTAL		**101,149**	**216,569**

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Tertiary	0	0.00	124,500	3,346
	1	0.08		
	2	0.17	8,904	1,484
	5	0.42		
	6	0.50	43,272	33,125
	15	1.25		
	16	1.33	5,613	8,499
	25	2.08		
	26	2.17	0.00	0.00
	35	2.92		
	36	3.00		
	60	5.00		
	TOTAL		**182,289**	**46,453**

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Paleozoic	0	0.00	23,052	1,921
	1	0.08		
	2	0.17	87,918	15,417
	5	0.42		
	6	0.50	100,499	105,959
	15	1.25		
	16	1.33	204,497	348,515
	25	2.08		
	26	2.17	75,859.21	191,354.22
	35	2.92		
	35	2.92	9,513.47	30,040.68
	60	5.00		
	TOTAL		**501,339**	**693,207**
	Snake Salt River Basin TOTAL		***2,848,124***	***2,620,738***

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Volcanic	0	0.00	31	3
	1	0.08		
	2	0.17	77,575	15,070
	5	0.42		
	6	0.50	116,972	131,911
	15	1.25		
	16	1.33	264,238	456,158
	25	2.08		
	26	2.17	40,185	94,687
	35	2.92		
	35	2.92	0	0
	60	5.00		
	TOTAL		**499,001**	**697,828**

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

Table 6-3. Annual recharge statistics for Snake/Salt River Basin aquifer recharge zones.

Aquifer Recharge Zone	Recharge zone surface area (acres)	Percent of total basin surface area	"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth, in	
					feet	inches
Quaternary	1,018,153	35.75%	548,010	20.91%	0.538	6.5
Tertiary	182,289	6.40%	46,453	1.77%	0.255	3.1
Mesozoic	546,194	19.18%	418,671	15.98%	0.767	9.2
Paleozoic	501,339	17.60%	693,207	26.45%	1.383	16.6
Precambrian	101,149	3.55%	216,569	8.26%	2.141	25.7
Volcanic	499,001	17.52%	697,828	26.63%	1.398	16.8
Total, Volcanic through Quaternary zones	**2,848,124**	**100.00%**	**2,620,738**	**100.00%**	**0.920**	**11.0**
Total, Sedimentary Aquifers (Paleozoic through Quaternary zones)	**2,247,974**	**79%**	**1,706,341**	**65%**	**0.736**	**8.8**

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

feet for the Wyoming portion of the basin (**table 8-2a**).

- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the Snake/Salt River Basin ranges from 0 to 54 inches (Hamerlinck and Arneson, 1998), with the lowest values occurring in the interior basins and the highest values in the upland drainages of the surrounding mountain ranges.

- Other factors controlling recharge may dominate locally (e.g., solution enhanced fractures); however, consideration of these factors should confirm the overall pattern of recharge and recharge efficiency.

- Recharge from precipitation to flat-lying Tertiary and Quaternary aquifers in the interior basin is generally less efficient than recharge to the exposed Paleozoic and volcanic aquifers in the mountainous areas. Recharge in the Snake/Salt River Basin is most efficient in higher elevation, Paleozoic terrains.

- Estimates of average annual recharge in the Snake/Salt River Basin are presented as a "best total" based on the cell-by-cell product of area and rate of recharge.

Chapter 7

Physical and chemical characteristics of hydrogeologic units in the Snake-Salt River Basin

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

The physical and chemical characteristics of hydrogeologic units in the Snake River Basin (Snake/Salt River Basin) are described in this chapter of the report. For descriptive and summary purposes, wells from which physical and chemical characteristics were obtained were grouped and summarized using six broad "geographic regions" shown in **figures 7-1** and **7-2**. The Gros Ventre, Teton, and Washakie Ranges are combined in one of the six broad geographic regions (the Northern Ranges) and the Green River and Hoback Basins are combined into one of six broad geographic regions (Green River and Hoback Basins) described below, but are shown separately on **figures 7-1** and **7-2**. The Absaroka, Wind River Basin, and Wind River Mountain geographic areas also are shown on **figures 7-1** and **7-2**, but are not included in the six broad geographic regions because no groundwater-quality data were available for the Absaroka and Wind River Basin geographic areas, and the Wind River Mountain geographic area was outside the Snake/Salt River Basin. The six 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 and others (1993, fig. 1); however, the areal extent of some regions also was refined using drainage areas (using 8-digit hydrologic unit codes). The six regions generally include the following geologic structures and associated geographic areas.

Yellowstone Volcanic Area:

- Madison Plateau
- Pitchstone Plateau
- Red Mountains
- Falls River Basin/Cascade Corner

Northern Ranges:

- Teton Range
- Washakie Range
- Gros Ventre Rang

Jackson Hole:

- Jackson Hole

Green River and Hoback Basins:

- Northernmost Green River Basin
- Hoback Basin

Overthrust Belt:

- Snake River Range
- Wyoming Range
- Salt River Range
- Gannett Hills

Star Valley:

- Star Valley

Lithostratigraphic and corresponding hydrostratigraphic (hydrogeologic) units in the Snake/Salt River Basin are shown on **plates 4**, **5**, and **6**. Lithostratigraphic units for specific structural areas identified on these plates were taken directly from the statewide Phanerozoic stratigraphic nomenclature chart of Love and others (1993).

For this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are summarized in tabular format (**pl. 3**). The original sources of the data used to construct the summary are listed 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 original reports—no reinterpretation of existing hydraulic data 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. Existing hydraulic data were converted

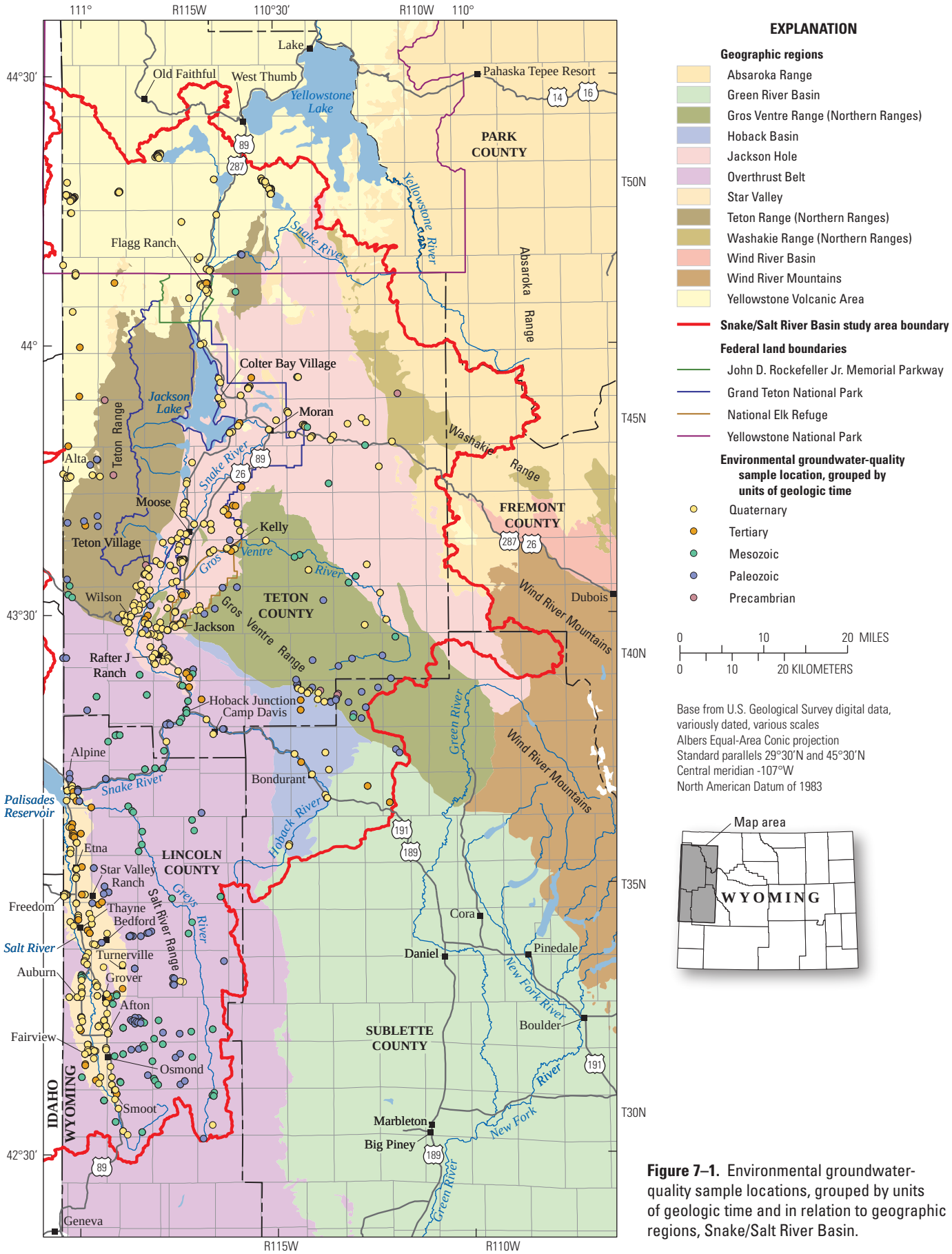


Figure 7–1. Environmental groundwater-quality sample locations, grouped by units of geologic time and in relation to geographic regions, Snake/Salt River Basin.

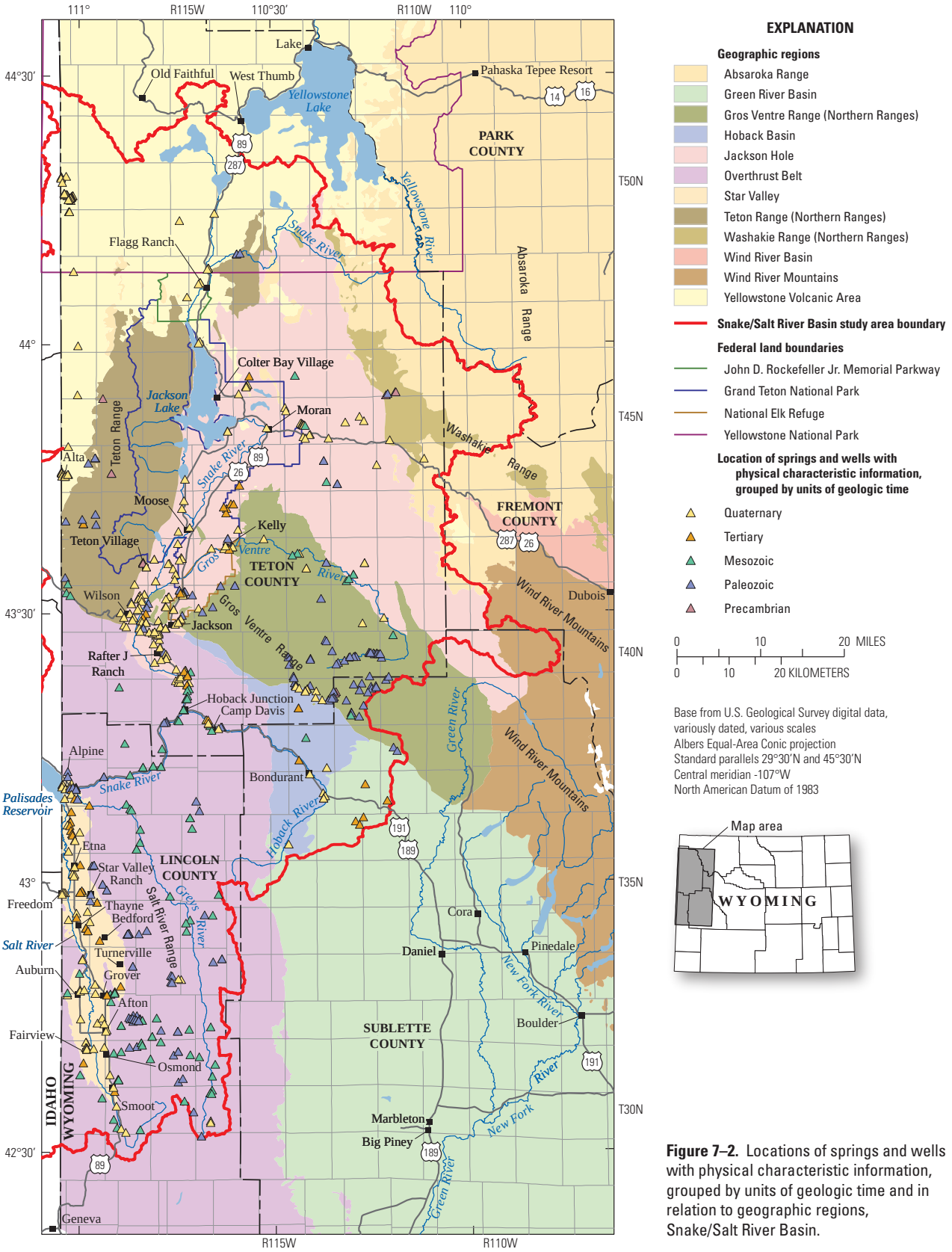


Figure 7–2. Locations of springs and wells with physical characteristic information, grouped by units of geologic time and in relation to geographic regions, Snake/Salt River Basin.

to consistent units to improve readability and facilitate comparability between different studies.

7.1 Snake/Salt River Basin

The physical and chemical characteristics of hydrogeologic units of Cenozoic, Mesozoic, Paleozoic, and Precambrian age in the Snake/Salt River Basin are described in this section of the report. Hydrogeologic units of the Snake/Salt River Basin are identified on **plates 4, 5,** and **6**. The areal extent of hydrogeologic units in the Snake/Salt River Basin is shown on **plate 2**. Many physical characteristic descriptions were modified from Bartos and Hallberg (2010), Clarey (2011), and Bartos and others (2012, 2014).

7.2 Cenozoic hydrogeologic units

Hydrogeologic units of Cenozoic (Quaternary and Tertiary) age are described in this section the report. Cenozoic hydrogeologic units are composed of both unconsolidated deposits such as sand and gravel (primarily of Quaternary age) and consolidated sediments (bedrock of Tertiary age) such as sandstone and conglomerate. Compared with aquifers of Mesozoic, Paleozoic, and Precambrian age, Cenozoic aquifers are the most used sources of groundwater. Cenozoic aquifers are used as a source of water for stock, domestic, industrial, irrigation, and public-supply purposes in the Snake/Salt River Basin.

7.2.1 Quaternary unconsolidated deposits

Where saturated and sufficiently permeable, unconsolidated sediments of Quaternary age in the Snake/Salt River Basin can contain aquifers. Saturated Quaternary unconsolidated deposits that contain aquifers (referred to herein as “Quaternary unconsolidated-deposit aquifers”) in the Snake/Salt River Basin typically include alluvium and colluvium (identified herein as "Quaternary alluvial aquifers"), terrace deposits (identified herein as "Quaternary terrace-deposit aquifers"), and glacial deposits (identified herein as "Quaternary glacial-deposit aquifers"). These aquifers can be highly productive locally and are the source of water for many shallow wells in the Snake/Salt River Basin. Quaternary unconsolidated-deposit aquifers are the most used sources of groundwater in the Snake/Salt River Basin for stock, domestic, industrial, irrigation, and public-supply purposes. The largest use of these aquifers occurs in the Snake River valley and the Salt River valley (also known as the Star Valley); both valleys coincide with much of the rural and urban population in the study area.

The physical and chemical characteristics of saturated Quaternary unconsolidated-deposits aquifers in the Snake/Salt River Basin are described in this section of the report.

In addition, a previously constructed groundwater-flow model of a Quaternary unconsolidated-deposit aquifer in the Snake/Salt River Basin is identified and briefly described.

Physical characteristics

Quaternary unconsolidated deposits are 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 (Lines and Glass, 1975; Cox, 1976; Ahern and others, 1981; Love and others, 1992; Sunrise Engineering, 2003, 2009). In places, unconsolidated deposits of Quaternary age are intermixed with unconsolidated deposits of Tertiary age (for example, Love, 2001a, b, c). Several types of unconsolidated deposits of Quaternary age are present in the Snake/Salt River Basin (**pls. 1** and **2**). Collectively, the Quaternary unconsolidated deposits can be thought of as "valley fill" or "basin fill" because the deposits partly fill many of the narrow and broad river valleys of the Snake/Salt River Basin formed by faulting, erosion, or both, through which the Snake and Salt Rivers and related tributaries flow. The deposits commonly grade into and (or) overlie one another and are bounded laterally or vertically by (rest on top of) bedrock. 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.

Estimates of the maximum thickness of Quaternary

unconsolidated deposits are uncommon for many areas in the Snake/Salt River Basin and available estimates vary substantially by location, primarily because few wells in most areas fully penetrate the deposits. Behrendt and others (1968) estimated that Holocene deposits (less than 10,000 years before present) are as thick as 400 feet (ft) in the Jackson Hole area. North of the Overthrust Belt, Cox (1976, Sheet 1) estimated that the maximum thickness of alluvium, terrace deposits, and glacial outwash deposits was about 200 ft. Lines and Glass (1975, Sheet 1) noted that wells completed in Quaternary alluvial deposits (composed of flood-plain alluvium and alluvial fans) in the Overthrust Belt generally were less than 200 ft in depth, and thus, the maximum thickness was unknown. Because thicknesses vary substantially by location, individual geologic maps should be consulted to determine thickness ranges for Quaternary unconsolidated deposits in areas of interest in the Snake/Salt River Basin.

Quaternary-age alluvium is composed of unconsolidated, poorly to well sorted mixtures of clay, silt, sand, and gravel deposited along streams, primarily as channel-fill and flood-plain deposits. Locally, alluvium can include alluvial fan and terrace deposits, valley side colluvium or talus, reworked glacial outwash deposits, and sediments deposited in small bogs, lakes, or deltas. Alluvium commonly grades laterally and vertically into other adjacent Quaternary unconsolidated deposits, typically terrace deposits; consequently, it is often difficult to determine where to differentiate the different types of Quaternary unconsolidated deposits in the Snake/Salt River Basin. In addition, different investigators have not always been consistent when mapping/identifying ("lumping and splitting") the different types of Quaternary unconsolidated deposits. Furthermore, use of different scale geologic maps results in different groupings of the unconsolidated deposits.

Quaternary unconsolidated terrace deposits (also described as gravel, pediment, and fan deposits, terrace gravel deposits, or terrace, gravel, and fan deposits) are present in the Snake/Salt River Basin, primarily adjacent to the alluvium in river valleys (**pls. 1** and **2**). Like alluvium, terrace deposits are composed of unconsolidated sand and gravel, and less commonly of cobbles and boulders derived from older sedimentary and crystalline rocks; stratification and sorting varies, and coarser sediments commonly are interbedded/intermixed with finer-grained sediments such as clay and silt. The size of sediments composing the deposits is related primarily to the source of the eroded parent material and distance transported. The areal extent of terrace deposits generally is small, and the deposits typically are found along uplands bordering principal streams of the Snake/Salt River Basin (**pls. 1** and **2**); however, areally extensive deposits are found in some areas, most notably in Jackson Hole and Star Valley (**pls. 1** and **2**). Terrace deposits may be present in many different terrace levels alongside streams draining the basin and in adjacent upland areas. Terrace-deposit thickness varies substantially in the Snake/Salt River Basin and depends on stream or river valley association and location.

Colluvium is composed of unconsolidated and poorly sorted sediment ranging in size from silt to boulder-sized rocks mantling major stream valley sides, tributary stream valleys, and the bases of hillsides/hillslopes (Love and others, 1992). Colluvium generally is deposited by rainwash, sheet wash, or slow continuous downslope creep (Bates and Jackson, 1980). Locally, colluvium can include soil, gravel, and glacial drift. Colluvium commonly is included (mapped) with alluvium on geologic maps of the Snake/Salt River Basin. 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.

Quaternary alluvial fan deposits occur along the river valleys in the Snake/Salt River Basin (Love and others, 1992). The alluvial fan deposits are composed of unconsolidated, poorly sorted, alluvium and colluvium forming well defined fan-shaped deposits at mouths of tributary valleys. Like colluvium, Quaternary alluvial fan deposits commonly are included (mapped) with alluvium on geologic maps of the Snake/Salt River Basin.

Glaciation has affected many parts of the Snake/Salt River Basin. Sediments deposited during

glaciation (Quaternary glacial deposits) generally are till and moraine or outwash deposits, consisting of unconsolidated, unstratified to stratified, sorted to unsorted mixtures of rock fragments (including boulders), gravel, sand, silt, and clay deposited by alpine (mountain) glaciers (Love and others, 1992). Glacial till and moraine deposits are deposited directly by and underneath glaciers without subsequent reworking by meltwater (Bates and Jackson, 1980). Glacial outwash deposits are transported from glaciers by meltwater streams and deposited in front of or beyond the end moraine or the margin of an active glacier (Bates and Jackson, 1980). Quaternary glacial deposits may be considered aquifers and developed where sufficiently water saturated and permeable. Productive wells completed in glacial deposits in the Snake/Salt River Basin likely are completed in outwash deposits composed of permeable, stratified coarse sand and gravel because deposits comprising tills and moraines generally are much less permeable because of lack of stratification, poor sorting, and fine grain size (Whitehead, 1996).

Where saturated and permeable, Quaternary unconsolidated deposits can contain aquifers. Quaternary unconsolidated-deposit aquifers are small in areal extent and primarily occur in alluvium (commonly associated with colluvium and referred to herein as "alluvial aquifers"), terrace deposits (sometimes referred to as "terrace gravel deposits" or "terrace, gravel, and fan deposits" in some reports and referred to herein as "terrace-deposit aquifers") and glacial deposits (referred to herein as "glacial-deposit aquifers") along stream and river valleys and in adjacent upland areas in the Snake/Salt River Basin (**pls. 1** and **2**).

Although limited in areal extent, Quaternary unconsolidated-deposit aquifers (most commonly alluvial and terrace-deposit aquifers) are the most used and some of the most productive aquifers in the Snake/Salt River Basin (Lines and Glass, 1975; Cox, 1976; Ahern and others, 1981; Sunrise Engineering, 2003, 2009, and references therein). Much of the population in the Snake/Salt River Basin coincides with and directly overlies the Quaternary alluvial and terrace-deposit aquifers. Consequently, most wells completed in Quaternary unconsolidated-deposit aquifers are located close to and along streams and rivers, most commonly along parts of the Salt River (Star Valley) and the Snake River valley and associated tributaries (WSGS needs to add proper figure/map reference from earlier chapter here). Most irrigated lands in the Snake/Salt River Basin overlie Quaternary unconsolidated-deposit aquifers (Sunrise Engineering, 2003, Figures II-1 and II-2).

Groundwater in Quaternary unconsolidated-deposit aquifers in the Snake/Salt River Basin typically is unconfined (water-table conditions predominate). However, fine-grained sediments overlying coarse-grained permeable zones can result in locally confined conditions or overlying perched water tables at some locations in the Snake/Salt River Basin (for example, Walker, 1965).

Along the flood plains and stream valleys, aquifers in alluvium and associated terrace deposits typically are in hydraulic connection with one another and adjacent streams and rivers (Walker, 1965; Lines and Glass, 1975, Sheet 1; Hinckley Consulting and Jorgensen Engineering, 1994; Eddy-Miller and others, 1996, 2009, 2013b; Wyoming State Engineer's Office, 1995, 2005; Wheeler and Eddy-Miller, 2005;. In addition, Quaternary alluvial and terrace-deposit aquifers are in hydraulic connection with adjacent or underlying Tertiary bedrock aquifers at some locations.

An unconsolidated-deposit aquifer primarily composed of Quaternary alluvium and terrace deposits and limited glacial deposits, referred to herein as the Snake River alluvial aquifer, underlies much of the Jackson Hole area (Cox, 1976, Plate 3; Nolan and Miller, 1995; San Juan and Kolm, 1996; Nolan and others, 1998). The areal extent and generalized potentiometric surface of the aquifer are shown on **figure 7-3**. Nolan and Miller (1995) and Nolan and others (1998) informally named this aquifer the "Jackson aquifer." This aquifer provides much of the water used for stock, domestic, irrigation, industrial, and public-supply purposes in the area. Saturated aquifer thickness was estimated by Cox (1976, plate 3) to range from less than 50 ft to as much as 300 ft. Using a time-domain electromagnetic survey conducted mostly

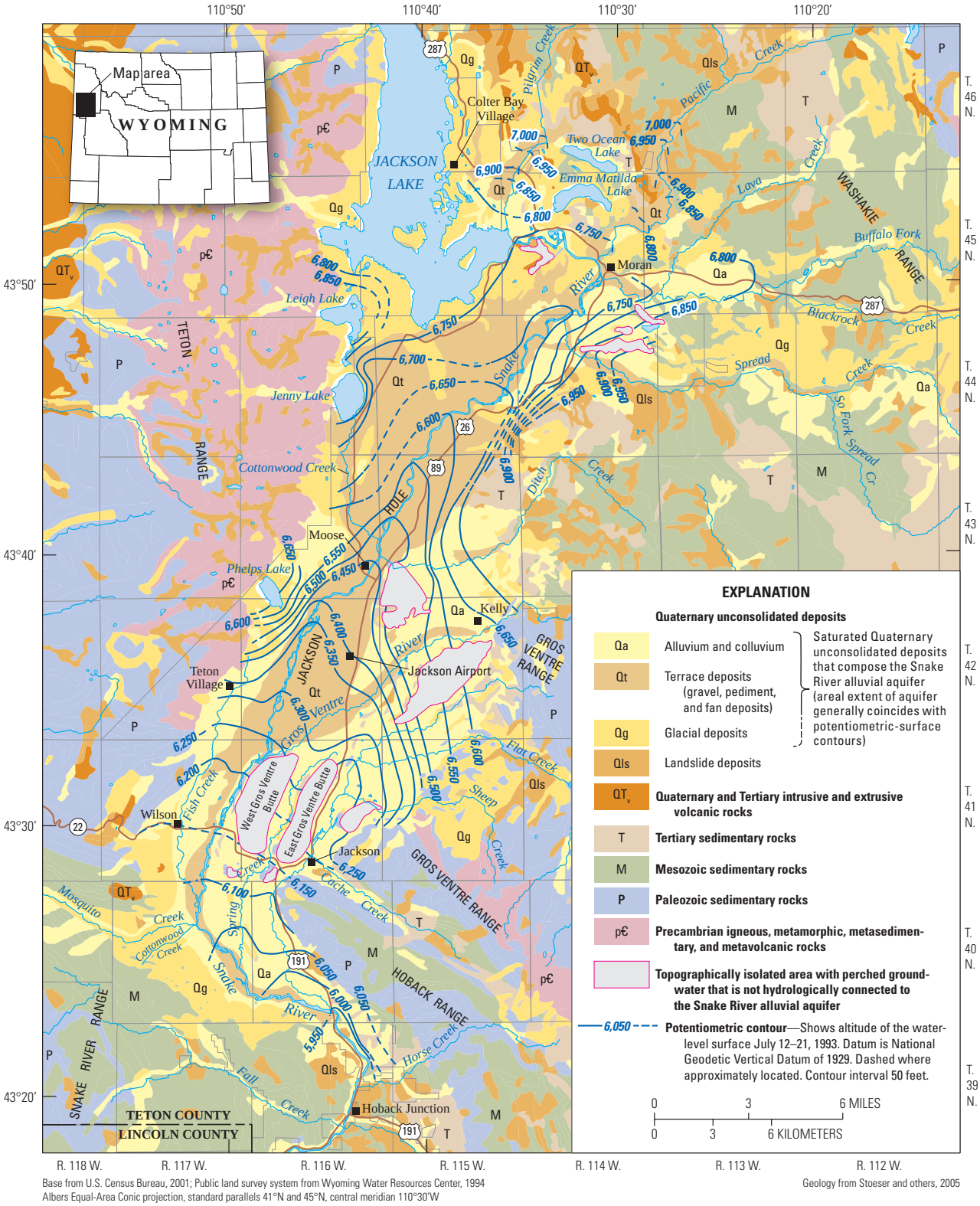


Figure 7–3. Areal extent and generalized potentiometric surface of the Snake River alluvial aquifer, Jackson Hole, Wyoming, July 12–21, 1993 (modified from Nolan and Miller, 1995, Plate 3).

in Grand Teton National Park, Nolan and Miller (1995) estimated that the depth of Quaternary unconsolidated deposits at nine locations within the areal extent of the aquifer ranged from about 380 to 2,400 ft. Using audio-magnetotellurics (a deep exploration electromagnetic method), Nolan and others (1998) estimated depth of the base of the aquifer for the southern part of the aquifer (area from about 4.5 miles north of Hoback Junction to less than 1 mile north of Teton Village). Estimated depth of the base of the aquifer for this area ranged from about 100 ft in the south, near the confluences of Spring Creek and Flat Creek with the Snake River, to about 700 ft in the west, near the town of Wilson, Wyoming; median depth of the base of the aquifer was estimated to be about 200 ft. Much of the aquifer is underlain by Quaternary unconsolidated lacustrine deposits and other finer grained, less permeable lithostratigraphic units (Cox, 1976, pl. 3; Nolan and Miller, 1995; Nolan and others, 1998).

Quaternary loess deposits, also defined as eolian deposits in some publications, consist of wind-blown, light gray, unconsolidated silt (Love and Albee, 1972). Saturated, loess deposits typically yield very small volumes of groundwater because of predominantly fine grain size. In some parts of the Snake/Salt River Basin, Quaternary loess deposits are intermixed with Quaternary lithified talus deposits. Quaternary lithified talus deposits (breccias) are composed of angular Paleozoic rock fragments (primarily eroded from the Madison Limestone) cemented by a white limey cement (Love and Albee, 1972). Locally, saturated loess and lithified talus deposits in the Snake/Salt River Basin may be sufficiently saturated and permeable to yield water to wells, as several wells likely completed in these deposits were inventoried as part of this study (**pl. 3**).

Quaternary landslide deposits are composed of masses of soil, sediment, and older bedrock that have moved downward under gravity and accumulated at the base of hillsides and steep slopes (Love and others, 1992; Love and Reed, 2000; Love and Albee, 1972). Quaternary landslide deposits in the Snake/Salt River Basin (**pls. 1** and **2**) are saturated at some locations. Lines and Glass (1975, Sheet 1) noted that landslide deposits (identified as "rock debris") in the Overthrust Belt likely were not a potential source of water because of poor sediment sorting and small saturated thickness. Cox (1976, Sheet 1) noted that wells completed in these deposits probably would not yield more than a few gallons per minute. Only one well completed in Quaternary landslide deposits was inventoried as part of this study, but springs commonly issue from the base of the Quaternary landslide deposits in the study area.

Hydrogeologic data describing the Quaternary unconsolidated deposits in the Snake/Salt River Basin (alluvial aquifers, terrace-deposit aquifers, glacial-deposit aquifers, landslide deposits, and loess deposits), including spring-discharge and well-yield measurements, and other hydraulic properties, are summarized on **plate 3**. Well yields and physical properties of Quaternary unconsolidated-deposit aquifers are highly variable (**pl. 3**), reflecting the variable size, sorting, and stratification of sediments comprising the deposits, as well as saturated thickness that changes in response to different amounts of aquifer recharge and discharge (water withdrawal). In some areas of the Snake/Salt River Basin, most notably in alluvium and terrace deposits of the Jackson Hole area (part of the Snake River alluvial aquifer), well yields, specific capacities, and conductivities/transmissivities are high because of large saturated thicknesses and coarse-grained deposits.

Because the areal extent of Quaternary unconsolidated-deposit aquifers coincides with most of the population and irrigated cropland in the Snake/Salt River Basin, these aquifers particularly are susceptible to effects from human activities (Hamerlinck and Arneson, 1998). Evidence of localized effects to groundwater quality in Quaternary unconsolidated-deposit aquifers by human activities in the Snake/Salt River Basin has been indicated by detection of elevated nitrate concentrations, as well as by low-level detections of organic compounds such as pesticides (Eddy-Miller and others, 1996; Eddy-Miller and Norris, 2000; Eddy-Miller and Remley, 2004; Sunrise Engineering, 2009; Eddy-Miller and others, 2013a). Hedmark and Young (1999) documented

groundwater-quality degradation from disposal of wastewater into sewage lagoons overlying Quaternary unconsolidated-deposit aquifers used to supply water for different uses in Grand Teton National Park and the John D. Rockefeller Memorial Parkway. Anti-icing/deicing compounds were found in the Snake River alluvial aquifer near the Jackson Hole Airport (Wright, 2013).

Recharge, discharge, and groundwater movement

Recharge to Quaternary unconsolidated-deposit aquifers primarily is from direct infiltration of precipitation (snowmelt and rain), snowmelt runoff, lakes, and ephemeral and perennial streamflow losses (Walker, 1965; Lines and Glass, 1975, Sheet 1; Cox, 1976; Ahern and others, 1981; Nelson Engineering, 1992; Wyoming State Engineer's Office, 1995, 2005; Hinckley Consulting and Jorgensen Engineering, 1994; Wheeler and Eddy-Miller, 2005; Eddy-Miller and others, 2009, 2013b; Wright, 2010, 2013). Infiltration of diverted surface water through unlined irrigation canals and ditches, from water applied to fields using flood and sprinkler irrigation, and discharge from adjacent and underlying bedrock aquifers also provide recharge in some areas (Walker, 1965; Lines and Glass, 1975, Sheet 1; Ahern and others, 1981; Sando and others, 1985; Hinckley Consulting and Jorgensen Engineering, 1994; Wyoming State Engineer's Office, 1995, 2005). In areas coinciding with population, additional recharge may occur from localized lawn watering, septic leach fields, and wastewater injection wells (Hinckley Consulting and Jorgensen Engineering, 1994). Most recharge occurs in the spring as a result of infiltration and percolation of rainfall, snowmelt, and snowmelt runoff (Walker, 1965; Lines and Glass, 1975, Sheet 1; Nelson Engineering, 1992; Hinckley Consulting and Jorgensen Engineering, 1994; Hedmark and Young, 1999; Wyoming State Engineer's Office, 1995, 2005; Eddy-Miller and others, 2009, 2013b; Wright, 2010, 2013). Some of the recharge to Quaternary unconsolidated-deposit aquifers from streams may occur as water infiltrates the heads of alluvial fans along the margins of stream valleys in the Snake/Salt River Basin (Walker, 1965; Lines and Glass, 1975, Sheet 1).

Water levels in Quaternary unconsolidated deposit aquifers in the Snake/Salt River Basin also can be affected by water-surface elevations in nearby reservoirs. In the Alpine Junction area (includes town of Alpine and adjacent unincorporated lands), groundwater-level fluctuations in the Quaternary unconsolidated deposits or Tertiary Salt Lake Formation in the area (difficult to differentiate these lithostratigraphic units in the subsurface in the vicinity of the town), or both have been correlated to changes in the water-surface elevation of nearby Palisades Reservoir (Sunrise Engineering, 1995).

In irrigated areas, water levels in the Quaternary unconsolidated-deposit aquifers in the Snake/Salt River Basin may increase in response to recharge from seasonal application of diverted surface water through flooding or sprinkler methods used to irrigate crops (Walker, 1965; Lines and Glass, 1975, Sheet 1; Cox, 1976; Ahern and others, 1981; Hinckley Consulting and Jorgensen Engineering, 1994; Wyoming State Engineer's Office, 1995). Water levels in some wells completed in Quaternary unconsolidated-deposit aquifers in Star Valley may be highest (shallowest) during the growing season when irrigation water recharges the aquifers, and water levels may be lowest (deepest) after irrigation has ceased during the winter when water is discharged from the aquifers (Walker, 1965).

Because of ongoing concerns about high (shallow) groundwater levels in the Snake River alluvial aquifer east of Fish Creek and west of the Snake River (area known as the west bank of the Snake River or Snake River west bank), the effects of potential recharge from residential ponds to the aquifer was investigated by Hinckley Consulting and Jorgensen Engineering (1994). Residential ponds are constructed into unconsolidated deposits composing the Snake River alluvial aquifer in this area to "enhance aesthetics, provide seasonal fisheries, create wildlife habitat, and provide recreational use" (Hinckley Consulting and Jorgensen Engineering, 1994, pl. 1). Study findings indicated that the ponds had little effect

on surrounding groundwater levels relative to the substantially larger normal seasonal and annual groundwater-level fluctuations measured in the aquifer (Hinckley Consulting and Jorgensen Engineering, 1994).

Discharge from Quaternary unconsolidated-deposit aquifers occurs from withdrawals by pumped wells and naturally by evapotranspiration, gaining streams, seeps, and spring flows (Walker, 1965; Lines and Glass, 1975, Sheet 1; Cox, 1976; Ahern and others, 1981; Nelson Engineering, 1992; Hinckley Consulting and Jorgensen Engineering, 1994; Wheeler and Eddy-Miller, 2005; Wyoming State Engineer's Office, 2005; Eddy-Miller and others, 2009, 2013b). Evapotranspiration from Quaternary unconsolidated-deposit aquifers is likely to be highest in the summer and in areas where the water table is at or near the land surface, such as in alluvium near streams.

Groundwater flow in the Quaternary alluvial aquifers generally is towards the center of the river or stream valley or generally in a downstream direction paralleling the direction of the surface-water flow in the river or streams, including as underflow parallel to streamflow (Lines and Glass, 1975, Sheet 1; Cox, 1976; Ahern and others, 1981; Nolan and Miller, 1995). In terrace-deposit aquifers, the direction of groundwater flow generally is similar to groundwater flow in Quaternary alluvial aquifers and is toward the principal surface drainage.

Several potentiometric-surface maps have been constructed showing the direction of horizontal groundwater flow in the Snake River alluvial aquifer (composed of saturated Quaternary alluvial, terrace, and glacial deposits along the Snake River and some of the valleys of tributaries to the Snake River; areal extent of aquifer shown in figure 7-3) (Cox, 1976, Sheet 3; Nolan and Miller, 1995) or parts of the aquifer in the Snake River west bank area (Wyoming State Engineer's Office, 2005). The generalized potentiometric-surface map of the Snake River alluvial aquifer in the Jackson Hole area constructed by Nolan and Miller (1995, Plate 3) is reproduced herein as figure 7-3.

Potentiometric-surface contours on the maps constructed by Cox (1976, Sheet 3) and Nolan and Miller (1995, Plate 3; reproduced herein as figure 7-3) show the general direction of regional groundwater flow; site-specific groundwater-flow directions could differ. Groundwater is assumed to flow in a direction perpendicular to the potentiometric-surface contours, from areas of high hydraulic head to areas of low hydraulic head. Groundwater-flow directions are not constant, and flow direction can change during different times of the year. Potentiometric-surface maps by Cox (1976, Sheet 3) and Nolan and Miller (1995, Plate 3, reproduced herein as figure 7-3) show that groundwater in the Snake River alluvial aquifer generally moves from topographically high areas toward the Snake River and southwest through the valley in the direction of the river.

Contours on potentiometric-surface maps in the immediate vicinity of streams can indicate gaining streams by pointing in an upstream direction (potentiometric surface above water in the stream) or losing streams by pointing in a downstream direction (potentiometric surface below water in the stream). General areas of streamflow loss to and gain from the Snake River alluvial aquifer can be visually identified on the maps of Cox (1976, Sheet 3) and Nolan and Miller (1995, Plate 3; reproduced herein as figure 7-3). Because the contours point in an upstream direction, the Snake River generally was gaining water from the aquifer throughout most of the valley at the time groundwater levels were measured to construct the maps (Cox, 1976, Sheet 3; Nolan and Miller, 1995, Plate 3). Cox (1976, Sheets 2, 3) used the contour map, in combination with streamflow loss and gain measurements for selected stream reaches, to determine that the Snake River and Buffalo Fork were gaining streams, Pilgrim and Cottonwood Creeks were losing streams, and the Gros Ventre River was neither gaining nor losing.

The Wyoming State Engineer's Office (2005, Figure 2) constructed a potentiometric-surface map for part of the Snake River alluvial aquifer in the west bank of the Snake River. The map was constructed using water levels measured in June

1998, and shows that groundwater in the west bank area generally moves southwest from the Snake River towards Fish Creek.

Wright (2011, 2013) examined groundwater levels and seasonal groundwater-level fluctuations of the Snake River alluvial aquifer at the Jackson Hole Airport. Large groundwater-level fluctuations associated with infiltration and percolation of spring precipitation and snowmelt were documented in both studies. Potentiometric-surface maps of the Snake River alluvial aquifer were constructed for the airport area as part of both studies.

Groundwater-flow model

A groundwater-flow model of the Snake River alluvial aquifer from Jackson Lake southward to the Snake River Canyon of the Snake River was constructed by San Juan and Kolm (1996). The unconfined aquifer was modeled using two layers, and was constructed using the then-current version of the finite-difference groundwater-flow model MODFLOW (McDonald and Harbaugh, 1988). The investigators used the groundwater-flow model to improve conceptualization and characterization of the aquifer with particular emphasis on using then-current geographic information system data management and analysis tools. Much of the hydrologic data used to construct the model was from Cox (1976). The model was constructed to simulate two-dimensional steady-state conditions, and the investigators concluded that refinement of both the conceptual and numerical models would be necessary to evaluate potential groundwater-management scenarios.

Chemical characteristics

The chemical characteristics of saturated Quaternary unconsolidated deposits in the Snake/Salt River Basin (Quaternary alluvial aquifers, terrace-deposit aquifers, glacial-deposit aquifers, landslide deposits, and loess and lithified talus deposits) are described in this section of the report.

7.2.1.1 Quaternary alluvial aquifers

The chemical characteristics of groundwater from Quaternary alluvial aquifers in the Snake/Salt River Basin are described in this section of the report. 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 (**appendices E–1** to **E–6**).

Yellowstone Volcanic Area
The chemical composition of Quaternary alluvial aquifers in the Yellowstone Volcanic Area (YVA) 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 E–1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–1, diagram A**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1; appendix F–1, diagram A**). TDS concentrations ranged from 131 to 248 mg/L, with a median of 147 mg/L.

Concentrations of some properties and constituents in water from Quaternary alluvial aquifers in the YVA 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 (both samples exceeded the USEPA MCL of 10 µg/L). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: fluoride (all 4 samples exceeded the SMCL of 2 mg/L) and aluminum (1 of 2 samples exceeded the lower SMCL limit of 50 µg/L and the upper SMCL limit of 200 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

Northern Ranges
The chemical composition of Quaternary alluvial aquifers in the Northern Ranges (NR) 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 E–2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–2, diagram A**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; Appendix F–2, diagram A**). TDS concentrations for the wells ranged from 160 to 267 mg/L, with a median of 233 mg/L. The TDS concentration for the spring was 159 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary alluvial aquifers in the NR 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.

Jackson Hole
The chemical composition of Quaternary alluvial aquifers in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs and 117 wells. Summary statistics calculated for available constituents are listed in **appendix E–3**. Major-ion composition in relation to TDS for water samples collected from wells is shown on a trilinear diagram (**appendix F–3, diagram A**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagram A**). The TDS concentration for one spring was 470 mg/L. TDS concentrations for the wells ranged from 52.0 to 628 mg/L, with a median of 250 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary alluvial aquifers in JH 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 in the spring samples.

Concentrations of some properties and constituents in water from wells completed in alluvial aquifers in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters from wells were suitable for domestic use, but concentrations of two constituents exceeded USEPA health-based standards: radon (all 11 samples exceeded the proposed MCL of 300 pCi/L, but none exceeded the AMCL of 4,000 pCi/L), and uranium (1 of 2 samples exceeded the MCL of 30 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: aluminum (1 of 13 samples exceeded the lower SMCL limit of 50 µg/L and the upper SMCL limit of 200 µg/L), iron (3 of 44 samples exceeded the SMCL of 300 µg/L), manganese (2 of 31 samples exceeded the SMCL of 50 µg/L), TDS (2 of 71 samples exceeded the SMCL of 500 mg/L), fluoride (1 of 71 samples exceeded the SMCL of 2 mg/L), sulfate (1 of 72 samples exceeded the SMCL of 250 mg/L), and pH (1 of 97 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents in water from wells completed in alluvial aquifers in JH exceeded State of Wyoming standards for agricultural and livestock use. One characteristic and one constituent in environmental water samples from wells were measured at concentrations greater than agricultural-use standards: sulfate (2 of 72 samples exceeded the WDEQ Class II standard of 200 mg/L) and SAR (1 of 68 samples exceeded the WDEQ Class II standard of 8). One characteristic (pH) was measured outside the range for livestock use (1 of 97 samples above upper WDEQ Class III limit of 8.5).

Green River and Hoback Basins
The chemical composition of Quaternary alluvial aquifers in the Green River and Hoback Basins (GH) was characterized and the quality evaluated on the basis of environmental water samples from

one spring and as many as eight wells. Summary statistics calculated for available constituents are listed in **appendix E–4**. Major-ion composition in relation to TDS for water samples collected from wells is shown on a trilinear diagram (**appendix F–4, diagram A**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4; appendix F–4, diagram A**). The TDS concentration for the spring was 250 mg/L. TDS concentrations for the wells ranged from 285 to 445 mg/L, with a median of 356 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary alluvial aquifers in the GH was suitable for most uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent (radon) exceeded health-based standards (the 1 sample analyzed for this constituent exceeded the proposed MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L) No State of Wyoming domestic, agriculture, or livestock water-quality standards were exceeded.

Overthrust Belt

The chemical composition of Quaternary alluvial aquifers in the Overthrust Belt (OTB) 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 E–5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–5, diagram A**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram A**). TDS concentrations for the wells ranged from 230 to 333 mg/L, with a median of 311 mg/L. Most environmental waters were suitable for domestic use, but concentrations of one constituent (radon) exceeded health-based standards (the 1 sample analyzed for this constituent exceeded the proposed MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L) No State of Wyoming domestic, agriculture, or livestock water-quality standards were exceeded.

Star Valley

The chemical composition of Quaternary alluvial aquifers in Star Valley (SV) was characterized and the quality evaluated on the basis of environmental water samples from as many as 83 wells. Summary statistics calculated for available constituents are listed in **appendix E–6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–6, diagram A**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–6; appendix F–6, diagram A**). TDS concentrations for the wells ranged from 198 to 589 mg/L, with a median of 262 mg/L.

Concentrations of some properties and constituents in water from wells completed in alluvial aquifers in SV 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 (all 6 samples exceeded the proposed USEPA MCL of 300 pCi/L, but none exceeded the AMCL of 4,000 pCi/L), nitrate (3 of 38 samples exceeded the USEPA MCL of 10 mg/L), and nitrate plus nitrite (3 of 51 samples exceeded the USEPA MCL of 10 mg/L. Concentrations of one constituent and one characteristic exceeded USEPA aesthetic standards for domestic use: iron (1 of 14 samples exceeded the SMCL of 300 µg/L) and TDS (1 of 47 samples exceeded the SMCL of 500 mg/L).

Concentrations of some properties and constituents in water from wells completed in alluvial aquifers in SV exceeded State of Wyoming standards for agricultural and livestock use. One constituent in environmental water samples that had concentrations greater than agricultural-use standards was chloride (2 of 46 samples exceeded the WDEQ Class II standard of 100 mg/L). No characteristics or constituents had concentrations that approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.2.1.2 Quaternary terrace-deposit aquifers

The chemical characteristics of groundwater from Quaternary terrace-deposit aquifers in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of 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 (**appendices E–1**, **E–2**, **E–3**, **E–5**, and **E–6**).

Yellowstone Volcanic Area
The chemical composition of Quaternary terrace-deposit aquifers in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for available constituents are listed in **appendix E–1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–1, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1; appendix F–1, diagram B**). TDS concentrations ranged from 143 to 198 milligrams per liter (mg/L), with a median of 192 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary terrace-deposit aquifers in the YVA 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.

Northern Ranges
The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from one spring and two wells. Individual constituent concentrations for available constituents are listed in **appendix E–2**. TDS concentrations measured in water from the spring (172 mg/L) and both wells (173 and 601 mg/L) indicate that the water is fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2**).

On the basis of the characteristics and constituents analyzed for, the quality of water from one spring issuing from Quaternary terrace-deposit aquifers in the NR was suitable for most uses. No characteristics or constituents measured in the spring sample approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Concentrations of some characteristics and constituents in water from wells completed in the Quaternary terrace-deposit aquifers in the NR 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 in one of the well samples exceeded USEPA health-based standards: fluoride (MCL of 4 mg/L). Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use in one of two well samples: TDS (SMCL of 500 mg/L) and fluoride (SMCL of 2 mg/L).

Concentrations of some characteristics and constituents in water from wells completed in the Quaternary terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in the NR. One characteristic and one constituent in environmental water samples from one of the wells had concentrations greater than agricultural-use standards: SAR (WDEQ Class II standard of 8) and chloride (WDEQ Class II standard of 100 mg/L). No characteristics or constituents had concentrations that approached or exceeded applicable State of Wyoming livestock water-quality standards.

Jackson Hole
The chemical composition of Quaternary terrace-deposit aquifers in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from one spring and as many as 22 wells. Summary statistics calculated for available constituents are listed in **appendix E–3**, and major-ion composition in

relation to TDS is shown on a trilinear diagram for the well samples (**appendix F–3, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagram B**). The TDS concentration for the spring was 173 mg/L.TDS concentrations for the wells ranged from 58.0 to 267 mg/L, with a median of 178 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from the one spring issuing from Quaternary terrace-deposit aquifers in JH 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.

Concentrations of some properties and constituents in water from wells completed in Quaternary terrace-deposit aquifers in JH 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 (radon) exceeded health-based standards (the 1 sample analyzed for this constituent exceeded the proposed MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L). Concentrations of two constituents and one characteristic exceeded USEPA aesthetic standards for domestic use: manganese (6 of 13 samples exceeded the SMCL of 50 µg/L), iron (3 of 16 samples exceeded the SMCL of 300 µg/L), and pH (one of 22 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents in water from wells completed in Quaternary terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in JH. The characteristic and constituent in environmental water samples from wells that had concentrations greater than agricultural-use standards were manganese (5 of 13 samples exceeded the WDEQ Class II standard of 200 µg/L) and SAR (1 of 20 samples exceeded the WDEQ Class II standard of 8). The value of one characteristic (pH) was outside the range for livestock-use standards (1 of 22 samples above upper WDEQ Class III limit of 8.5).

Overthrust Belt

The chemical composition of Quaternary terrace-deposit aquifers in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **appendix E–5**. The TDS concentration from the spring (231 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L). No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards, indicating the water was suitable for most uses.

Star Valley

The chemical composition of Quaternary terrace-deposit aquifers in Star Valley (SV) was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations are listed in **appendix E–6**. The TDS concentration from one well sample (206 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 terrace-deposit aquifers in the SV 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.

7.2.1.3 Quaternary glacial-deposit aquifers

The chemical characteristics of groundwater from Quaternary glacial-deposit aquifers in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of glacial-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 as quantile values (**appendices E–1** to **E–5**).

Yellowstone Volcanic Area

The chemical composition of aquifers in Quaternary glacial-deposit aquifers in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations for available constituents are listed in **appendix E–1**. The TDS concentration (91.0 mg/L) for the well sample indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–1**). On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary glacial-deposit aquifers in the YVA 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.

Northern Ranges

The chemical composition of groundwater in Quaternary glacial-deposit aquifers in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs and six wells. Individual constituent concentrations for available constituents are listed in **appendix E–2**. Major-ion composition in relation to TDS for wells is shown on a trilinear diagram (**appendix F–2, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram B**). The TDS concentrations for the springs were 173 and 219 mg/L. TDS concentrations for the wells ranged from 162 to 228 mg/L, with a median of 178 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary glacial-deposit aquifers in the NR 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.

Jackson Hole

The chemical composition of Quaternary glacial-deposit aquifers in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from as many as 4 springs and 37 wells. Summary statistics calculated for available constituents are listed in **appendix E–3**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–3, diagrams C and D**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagrams C and D**). The TDS concentrations for the springs ranged from 78.0 to 312 mg/L, with a median of 232 mg/L. TDS concentrations for the wells ranged from 18.0 to 378 mg/L, with a median of 176 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary glacial-deposit aquifers in JH 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.

Concentrations of some properties and constituents in water from wells completed in the Quaternary glacial-deposit aquifers in JH 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 (one of two samples exceeded the proposed USEPA MCL of 300 pCi/L and the AMCL of 4,000 pCi/L). Concentrations of two constituents and one characteristic exceeded USEPA aesthetic standards for domestic use: manganese (2 of 7 samples exceeded the SMCL of 50 µg/L), iron (2 of 16 samples exceeded the SMCL of 300 µg/L), and pH (2 of 37 samples below lower SMCL limit of 6.5).

Concentrations of some characteristics and constituents in water from wells in Quaternary glacial-deposit aquifers exceeded State of Wyoming

standards for agricultural and livestock use in JH. One constituent (manganese) was measured in environmental water samples from wells at concentrations greater than agricultural-use standards (1 of 7 samples exceeded the WDEQ Class II standard of 200 µg/L). One characteristic (pH) was measured at values outside the range for livestock-use standards (2 of 37 samples below lower WDEQ Class III limit of 6.5).

Green River and Hoback Basins
The chemical composition of Quaternary glacial-deposit aquifers in the Green River and Hoback Basins (GH) was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in **appendix E–4**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–4, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4; appendix F–4, diagram B**). TDS concentrations for the springs ranged from 205 to 228 mg/L, with a median of 224 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary glacial-deposit aquifers in the GH 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.

Overthrust Belt
The chemical composition of Quaternary glacial-deposit aquifers in the Overthrust Belt (OTB) 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 E–5**. TDS concentrations from two springs (149 and 215 mg/L) indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary glacial-deposit aquifers in the OTB 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 Quaternary landslide deposits

The chemical characteristics of groundwater from Quaternary landslide deposits in the Snake/Salt River Basin 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–2** to **E–5**).

Northern Ranges
The chemical composition of groundwater in Quaternary landslide deposits in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from three springs and one well. Individual constituent concentrations for available constituents are listed in **appendix E–2**, and major-ion composition in relation to TDS is shown on a trilinear diagram for the spring samples (**appendix F–2, diagram C**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram C**). TDS concentrations for the three springs ranged from 79.8 to 276 mg/L, with a median of 127 mg/L. The TDS concentration for the well sample was 495 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary landslide deposits in the NR was suitable for most uses. No characteristics or constituents in the spring samples approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Concentrations of some characteristics and constituents in water from Quaternary landslide deposits in the well sample in the NR 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. One characteristic (pH) exceeded the aesthetic standard for domestic use in the one well sample (pH above upper USEPA SMCL limit of 8.5).

Concentrations of some characteristics and constituents in water from the well completed in Quaternary landslide deposits exceeded State of Wyoming standards for agricultural and livestock use in the NR. One characteristic (SAR) was measured in the well sample at a concentration greater than the agricultural-use standard (WDEQ Class II standard of 8). One characteristic (pH) was measured at values greater than the upper livestock-use standard (above upper WDEQ Class III limit of 8.5).

Jackson Hole
The chemical composition of Quaternary landslide deposits in Jackson Hole (JH) was characterized and the quality evaluated on the basis of an environmental water sample from one spring. Individual constituent concentrations are listed in **appendix E–3**. The TDS concentration from the spring (179 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 Quaternary landslide deposits in JH 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.

Green River and Hoback Basins
The chemical composition of Quaternary landslide deposits in the Green River and Hoback Basins (GH) was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in **appendix E–4**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–4, diagram C**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4; appendix F–4, diagram C**). TDS concentrations for the springs ranged from 93.0 to 179 mg/L, with a median of 139 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from Quaternary landslide deposits in the GH 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.

Overthrust Belt
The chemical composition of Quaternary landslide deposits in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **appendix E–5**. The TDS concentration from the spring (234 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 the one spring issuing from Quaternary landslide deposits in the OTB 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.

7.2.1.5 Quaternary loess and lithified talus deposits

The chemical characteristics of groundwater from Quaternary loess and lithified talus deposits in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of Quaternary loess and lithified talus deposits 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–3**).

Jackson Hole
The chemical composition of Quaternary loess and lithified talus deposits in Jackson Hole (JH) 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 E–3**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–3, diagram E**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagram E**). TDS concentrations for the wells ranged from 130 to 469 mg/L, with a median of 165 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from wells completed in Quaternary loess and lithified talus deposits in JH 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.

7.2.2 Leidy Formation

The Quaternary-age Leidy Formation (**pl. 5**) consists of very fine-grained, chocolate-brown, pink, and gray clay, laminated in part, interbedded with gray sand; lenticular quartzite pebble gravels; and basal quartzite boulder conglomerate in some places (Love and others, 1992). The Leidy Formation intertongues laterally with glacial drift and outwash deposits, and reported thickness ranges from 0 to 450 ft (Love and others, 1992). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit.

7.2.3 Quaternary and Tertiary volcanic rocks

Quaternary and Tertiary volcanic rocks are composed of intrusive igneous rocks, extrusive igneous rocks (primarily basalt and rhyolite), and beds of tuff and volcanic ash classified as many different lithostratigraphic units (**pls. 4, 5,** and **6**). Lithostratigraphic units composed either partially or entirely of tuff and volcanic ash in the Absaroka Volcanic Supergroup also could be classified as sedimentary rocks composed of volcaniclastic sediments, but they are grouped herein with the Quaternary and Tertiary volcanic rocks for convenience (for example, Wiggins Formation shown on **plate 6**). Quaternary and Tertiary volcanic rocks are essentially undeveloped in the Snake/Salt River Basin because they occur primarily in sparsely populated areas with no major population centers. Much of the areal extent of these rocks is within the boundary of Yellowstone National Park (**pls. 1** and **2**). Most investigations related to Quaternary and Tertiary volcanic rocks have been of thermal waters and related features in Yellowstone National Park (Gooch and Whitfield, 1888; Weed, 1889; Schlundt and Moore, 1909; Stearns and others, 1937; Fix, 1949; Morey and others, 1961; Marler, 1964; Rowe and others, 1965, 1973; Fournier and Rowe, 1966; Fournier and Truesdell, 1970; Fournier and Morgenstern, 1971; Marler and White, 1975; Thompson and others, 1975; Truesdell and Fournier, 1976a,b; Truesdell and others, 1977, 1978; Bargar, 1978; Pearson and Truesdell, 1978; Stauffer and Thompson, 1978, 1984; Thompson and Yadav, 1979; Stauffer and others, 1980; Thompson and Hutchinson, 1981; Friedman and Norton, 1982, 1990; Truesdell and Thompson, 1982; White and others, 1988; White, 1991; Rye and Truesdell, 1993, 2007; Fournier and others, 1994; Ball, Nordstrom, Cunningham, and others, 1998; Ball, Nordstrom, Jenne, and others, 1998; Ball and others, 2001, 2002; Gemery-Hill and others, 2007).

Information describing the physical and chemical characteristics of Quaternary and Tertiary volcanic rocks is sparse because few wells have been completed into the deposits. Hydrogeologic data describing Quaternary and Tertiary volcanic rocks in the Snake/Salt River Basin, including spring-discharge measurements and other hydraulic properties, are summarized on **plate 3**. Much of the information describing the characteristics of Quaternary and Tertiary volcanic rocks is from springs (commonly hot springs) issuing from the deposits (**pl .3; appendices E** and **F**).

Previous investigators have speculated that aquifer potential is poor (Wyoming Water Planning Program, 1972, Table III-2) or marginal (WWC Engineering and others, 2007, Figure 4-9). Other investigators have noted aquifer development potential is limited to localized areas with favorable

hydrogeologic characteristics, and widespread development was unlikely because the rocks occur mostly within the boundaries of Yellowstone National Park and areas that are geographically inaccessible and located away from any substantial population (Cox, 1976, Sheet 1; Whitehead, 1996; Bartos and others, 2012). Cox (1976, Sheet 1) speculated on the potential well yield of the various Quaternary and Tertiary volcanic rocks and noted that the Yellowstone Group may yield a few tens of gallons per minute per well from porous and fracture zones" (rhyolitic ash, welded tuff, lava flows, breccia, and volcanic glass) or "may yield a few tens of gallons per minute per well from brecciated zones and fractures" (basalt lava flows). The investigator (Cox, 1976, Sheet 1) also speculated that the Absaroka Volcanic Supergroup, composed of andesitic, basaltic, and dacitic volcaniclastic rocks, "probably would not yield more than a few gallons per minute per well." Large springs issuing from Quaternary and Tertiary volcanic rocks in some areas indicate that permeability locally can be high, but is likely extremely variable because of widely varying rock types (Whitehead, 1996). In most areas, yields of wells completed in Quaternary and Tertiary volcanic rocks likely would only be adequate for domestic use (Whitehead, 1996).

Chemical characteristics

The chemical characteristics of saturated Quaternary and Tertiary volcanic rocks in the Snake/Salt River Basin (Quaternary basalt flows, Quaternary rhyolite flows, Yellowstone Group, and Tertiary volcanic rocks) are described in this section of the report.

7.2.3.1 Quaternary basalt flows

The chemical characteristics of groundwater from Quaternary basalt flows in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of Quaternary basalt flows 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–1**).

Yellowstone Volcanic Area
The chemical composition of aquifers in Quaternary basalt flows in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations for available constituents are listed in **appendix E–1**. The TDS concentration (69.0 mg/L) from the well indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–1**). On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary basalt flows in the YVA 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.

7.2.3.2 Quaternary rhyolite flows

The chemical characteristics of groundwater from Quaternary rhyolite flows in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of Quaternary rhyolite flows 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–1**).

Yellowstone Volcanic Area
The chemical composition of Quaternary rhyolite flows in the YVA was characterized and the quality evaluated on the basis of environmental water samples from as many as 75 hot springs. Summary statistics calculated for available constituents are listed in **appendix E–1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**appendix F–1, diagram C**). TDS concentrations indicated that waters from one-half the hot springs were fresh (TDS concentrations less than or equal to 999 mg/L), and waters from the remaining one-half of the hot springs were slightly saline (1,000 to 2,999 mg/L) (**appendix E–1; appendix F–1, diagram C**). TDS concentrations for the hot

springs ranged from 298 to 1,470 mg/L, with a median of 1,000 mg/L.

Concentrations of some properties and constituents in water from rhyolite flows in the YVA hot springs 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 four constituents exceeded health-based standards: arsenic (the one sample analyzed for this constituent exceeded the USEPA MCL of 10 µg/L), mercury (the one sample analyzed for this constituent exceeded the MCL of 2 µg/L), fluoride (74 of 75 samples exceeded the USEPA MCL of 4 mg/L), and boron (1 of 75 samples exceeded the USEPA LHA of 6,000 µg/L). Concentrations of four constituents and two characteristics exceeded USEPA aesthetic standards for domestic use: aluminum (all 22 samples exceeded the lower SMCL standard of 50 µg/L and 12 of 22 samples exceeded the upper SMCL standard of 200 µg/L), fluoride (74 of 75 samples exceeded the SMCL of 2 mg/L), TDS (68 of 74 samples exceeded the SMCL of 500 mg/L), manganese (17 of 24 samples exceeded the SMCL of 50 µg/L), pH (9 of 73 samples below lower SMCL limit of 6.5 and 8 of 73 samples above upper SMCL limit of 8.5), and chloride (9 of 75 samples exceeded the SMCL of 250 mg/L).

Concentrations of some characteristics and constituents in water from hot springs in rhyolite flows exceeded State of Wyoming standards for agricultural and livestock use in the YVA. The characteristics and constituents in environmental water samples from hot springs that had concentrations greater than agricultural-use standards were mercury (one sample analyzed for this constituent exceeded the WDEQ Class II standard of 0.05 µg/L), SAR (71 of 74 samples exceeded the WDEQ Class II standard of 8), boron (71 of 75 samples exceeded the WDEQ Class II standard of 750 µg/L), chloride (45 of 75 samples exceeded the WDEQ Class II standard of 100 mg/L), lithium (7 of 73 samples exceeded the WDEQ Class II standard of 2,500 µg/L), manganese (2 of 24 samples exceeded the WDEQ Class II standard of 200 µg/L), and pH (2 of 73 samples above upper WDEQ Class II limit of 9). One characteristic and one constituent had values outside the range for livestock-use standards: pH (9 of 73 samples below lower WDEQ Class III limit of 6.5 and 8 of 73 samples above upper limit of 8.5) and boron (1 of 75 samples exceeded the WDEQ Class III standard of 5,000 µg/L).

The chemical composition of Quaternary rhyolite flows in the Yellowstone Volcanic Area (YVA) also was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs. Individual constituent concentrations are listed in **appendix E–1**. TDS concentrations (26.0 and 54.0 mg/L) indicated that both waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1**). On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary rhyolite flows in the YVA was suitable for most uses. One characteristic (pH) was measured in both samples at values outside the range for USEPA aesthetic standards for domestic use and WDEQ livestock-use standards (below lower USEPA SMCL and WDEQ Class III limit of 6.5).

7.2.3.3 Yellowstone Group

The chemical characteristics of groundwater from the Yellowstone Group in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Yellowstone Group 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–1** and **F–1**).

Yellowstone Volcanic Area

The chemical composition of water from the Yellowstone Group in the YVA was characterized and the quality evaluated on the basis of environmental water samples from as many as 11 hot springs. Summary statistics calculated for available constituents are listed in **appendix E–1**. Major-ion composition in relation to TDS is shown on trilinear diagrams (**appendix F–1, diagram D**). TDS concentrations indicated

that waters ranged from slightly saline (10 of 11 samples, concentrations between 1,000 to 2,999 mg/L) to fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1; appendix F–1, diagram D**). TDS concentrations in samples from the hot springs ranged from 734 to 1,430 mg/L, with a median of 1,210 mg/L.

Concentrations of some properties and constituents measured in water from hot springs issuing from the Yellowstone Group in the YVA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of five constituents measured in environmental waters exceeded health-based standards: antimony (all 4 samples exceeded the USEPA MCL of 6 µg/L), arsenic (all 4 samples exceeded the USEPA MCL of 10 µg/L), fluoride (all 11 samples exceeded the USEPA MCL of 4 mg/L), molybdenum (all 4 samples exceeded the USEPA LHA of 40 µg/L), and beryllium (2 of 4 samples exceeded the USEPA MCL of 4 µg/L). Concentrations of two characteristics and three constituents exceeded USEPA aesthetic standards for domestic use: TDS (all 11 samples exceeded the SMCL of 500 mg/L), fluoride (all 11 samples exceeded the SMCL of 2 mg/L), aluminum (3 of 4 samples exceeded the lower SMCL standard of 50 µg/L and 2 of 4 samples exceeded the upper SMCL standard of 200 µg/L), chloride (7 of 11 samples exceeded the SMCL of 250 mg/L), and pH (3 of 10 samples above upper SMCL limit of 8.5 and 1 of 10 samples below lower limit of 6.5).

Concentrations of some characteristics and constituents measured in water from hot springs issuing from the Yellowstone Group exceeded State of Wyoming standards for agricultural and livestock use in YVA. Characteristics and constituents measured in environmental water samples from hot springs at concentrations greater than agricultural-use standards were SAR (all 11 samples exceeded the WDEQ Class II standard of 8), arsenic (all 4 samples exceeded the WDEQ Class II standard of 100 µg/L), chloride (all 11 samples exceeded the WDEQ Class II standard of 100 mg/L), lithium (all 11 samples exceeded the WDEQ Class II standard of 2,500 µg/L), boron (10 of 11 samples exceeded the WDEQ Class II standard of 750 µg/L), mercury (2 of 4 samples exceeded the WDEQ Class II standard of 0.05 µg/L), and pH (2 of 10 samples above upper WDEQ Class II limit of 9). One constituent and one characteristic had values outside the range for livestock-use standards: arsenic (all 4 samples exceeded the WDEQ Class III standard of 200 µg/L) and pH (3 of 10 samples above upper WDEQ Class III limit of 8.5 and 1 of 10 samples below lower limit of 6.5).

The chemical composition of the Yellowstone Group in the Yellowstone Volcanic Area (YVA) also was characterized and the quality evaluated on the basis of environmental water samples from as many as six springs and six wells. Summary statistics calculated for available constituents are listed in **appendix E–1**, and major-ion composition in relation to TDS is shown on trilinear diagrams (**appendix F–1, diagrams E** and **F**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1; appendix F–1, diagrams E** and **F**). The TDS concentrations for the springs ranged from 22.0 to 133 mg/L, with a median of 55.0 mg/L. TDS concentrations for the wells ranged from 133 to 209 mg/L, with a median of 150 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Yellowstone Group in YVA was suitable for most uses. The concentration of one constituent (manganese) in one of two well samples analyzed for that constituent exceeded the USEPA aesthetic standards for domestic use (SMCL of 50 µg/L).

Northern Ranges

The chemical composition of the Yellowstone Group in the Northern Ranges (NR) 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 E–2**. The TDS concentration measured in the spring sample was 61 mg/L and indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–2**). TDS was not measured in the two well samples. However, specific conductance was measured in both well samples, and both values (392 and 483 microsiemens

per centimeter at 25 degrees Celsius, **appendix E–2**) would be much smaller than 999 mg/L when converted into equivalent TDS values by multiplying by 0.60 (Hem, 1985), indicating that both waters were fresh. On the basis of the characteristics and constituents analyzed for, the quality of water from the Yellowstone Group in the NR 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.

7.2.3.4 Tertiary intrusive rocks

The chemical characteristics of groundwater from Tertiary intrusive rocks in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Tertiary intrusive 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 (**appendices E–2** and **E–3**).

Northern Ranges
The chemical composition of the Tertiary intrusive rocks in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **appendix E–2**. The TDS concentrations (296 and 306 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Tertiary intrusive rocks in NR was suitable for most uses. No characteristics or constituents approached or exceeded applicable State of Wyoming domestic or livestock water-quality standards.

Jackson Hole
The chemical composition of the Tertiary intrusive rocks in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **appendix E–3**. The TDS concentrations (275 and 288 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for, the quality of water from Tertiary intrusive rocks in JH was suitable for most uses. Concentrations of one constituent exceeded health-based standards: radon (the 1 sample analyzed for this constituent exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L). Manganese was measured in one of the two well samples, and the concentration exceeded the USEPA aesthetic standard for domestic use (SMCL of 50 µg/L) and the State of Wyoming agricultural-use standard (WDEQ Class II standard of 200 µg/L).

7.2.3.5 Quaternary obsidian gravel and sand deposits

The physical and chemical characteristics of Quaternary obsidian gravel and sand deposits in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

One well completed in Quaternary unconsolidated deposits composed of gravel and sand with some silt and clay (Lowry and Gordon, 1964, p. 33) was inventoried as part of this study. The investigators reported that the unconsolidated deposits were overlain by rhyolite. Based on currently used lithostratigraphic terminology, the rhyolite overlying the unconsolidated deposits was interpreted herein to be the Lava Creek Tuff (Member B) of the Yellowstone Group (**pl. 6**). The gravel and sand-sized sediments were composed primarily of angular obsidian, so these deposits were informally named "Quaternary obsidian gravel and sand deposits" herein to reflect their unique composition and to differentiate them from other Quaternary unconsolidated deposits. Thickness of these deposits was at least 50 ft in the inventoried well. Existing hydrogeologic data for the well completed in these deposits, including well-yield and other hydraulic properties, are summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from Quaternary obsidian gravel and sand deposits in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of Quaternary obsidian gravel and sand deposits is described in terms of the water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**table 5-2)**.

Yellowstone Volcanic Area
The chemical composition of aquifers in Quaternary obsidian gravel and sand deposits in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations for available constituents are listed in **appendix E–1**. The TDS concentration (183 mg/L) from the well indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–1**). On the basis of the characteristics and constituents analyzed for, the quality of water from Quaternary obsidian gravel and sand deposits in the YVA was suitable for most uses. One constituent (fluoride) exceeded the USEPA aesthetic standard for domestic use (SMCL of 2 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.4 Tertiary hydrogeologic units

The physical and chemical characteristics of Tertiary-age hydrogeologic units are described in this section of the report. Stock, domestic, and public-supply wells are completed in these units in the Snake/Salt River Basin. Tertiary hydrogeologic units are composed of lithostratigraphic units ranging from Pliocene to Paleocene in age (**pls. 4, 5,** and **6**). The Upper Cretaceous to Paleocene-age Pinyon Conglomerate (**pls. 5** and **6**) is described in this section for convenience. Tertiary hydrogeologic units are composed of nonmarine (continental) mixtures of shale, mudstone, siltstone, sandstone, conglomerate, lacustrine limestone, volcanic tuff, and other lithologies. Tertiary lithostratigraphic units commonly interfinger with other formations and lithologies. These units are relatively flat-lying and unconformably overlie eroded and older bedrock formations.

7.2.4.1 Heart Lake Conglomerate

The Pliocene Heart Lake Conglomerate (**pl. 6**) consists of abundant gray limestone and dolomite clasts, and sparse rhyolite and quartz clasts in a talc and clay matrix (Love and Christiansen, 1985). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.2 Shooting Iron Formation

The Pliocene Shooting Iron Formation (**pl. 5**) consists of pink, red, green, yellow, dark-gray, and brown bentonitic, mollusk-bearing, lacustrine and fluvial claystone; gray and yellow tuffaceous sandstone and siltstone; and pebble conglomerate of volcanic rock fragments in a bentonitic matrix (Love and others, 1992). Maximum thickness of the Shooting Iron Formation is greater than 100 ft (Love and others, 1992). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.3 Salt Lake aquifer

The physical and chemical characteristics of the Salt Lake aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

Saturated and permeable parts of the Pliocene and Miocene Salt Lake Formation compose the Salt Lake aquifer in the Snake/Salt River Basin (**pl. 4**). The Salt Lake Formation consists of pale reddish gray poorly to well-cemented conglomerate, sandstone, siltstone, clay/claystone, and beds of white volcanic ash (tuff) (Rubey, 1973a,b; Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey and others, 1980; Ahern and others, 1981, Table IV-1). Reported maximum thickness of

the Salt Lake Formation in the Overthrust Belt is 1,000 ft (Lines and Glass, 1975, Sheet 1). The Salt Lake Formation is present in the structurally down-dropped valley floors within the Snake/Salt River Basin, most notably in the Star Valley area (Rubey, 1973a,b).

The Salt Lake Formation was classified as a major aquifer by Ahern and others (1981) and in the Statewide Framework Water Plan (WWC Engineering and others, 2007), and that definition was retained herein (**pl. 4**). Springs issuing from and wells completed in the aquifer provide water for domestic and public-supply use in the Snake/Salt River Basin (Forsgren Associates, 1991c, e, f, 1992, 1995; Trihydro Corporation, 1993a; Rendezvous Engineering, 2002; Rendezvous Engineering, PC, and Hinckley Consulting, 2009; Sunrise Engineering, 2009), primarily in Star Valley where the unit commonly underlies Quaternary unconsolidated deposits (**pl. 1**). Hydrogeologic data describing the Salt Lake aquifer in the Snake/Salt River Basin, including spring-discharge and well-yield measurements and other hydraulic properties, are summarized on **pl. 3**.

Salt Lake Formation permeability is both primary and secondary and highly localized. Lines and Glass (1975, Sheet 1) noted that conglomerates in the Salt Lake Formation were well cemented and poorly sorted, and consequently had little primary permeability; however, the investigators noted secondary permeability development may occur in areas where the formation is fractured, as exemplified by spring discharges as large as 8,000 gallons per minute (gal/min) from Flat Creek Springs, which is a spring issuing from fractured conglomerate in the Salt Lake Formation and is used to provide water to the town of Thayne in Star Valley. Subsequent studies of the Salt Lake Formation conducted in relation to public water-supply exploration and development in Star Valley have indicated that both primary and secondary permeability can be sufficient for public water-supply development, although aquifer productivity was highly spatially variable and dependent on local aquifer characteristics such as lithology and amount of fracturing (Forsgren Associates, 1992, 1993b,c, 1995, 1997, 2008; TriHydro Corporation, 1993a; Sunrise Engineering, 1995, 2009; Rendezvous Engineering, PC, 2002; Rendezvous Engineering, PC, and Hinckley Consulting, 2009). Where the Salt Lake Formation is composed primarily of fine-grained rocks (clay/claystone, siltstone, and tuff) and is unfractured, permeability is small and the formation is not an aquifer. In areas where impermeable, the Salt Lake Formation in Star Valley may "act as a leaky confining layer to underlying aquifers" (Forsgren Associates, 1995, p. 3-2).

Recharge to the Salt Lake aquifer in the Star Valley area is from direct infiltration of precipitation (snowmelt and rain), runoff, streamflow losses, and irrigation losses (Forsgren Associates, 1995; Rendezvous Engineering, PC, and Hinckley Consulting, 2009). This recharge occurs directly on aquifer outcrops, as well as through overlying Quaternary unconsolidated deposits.

Chemical characteristics

The chemical characteristics of groundwater from the Salt Lake aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Salt Lake 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–5**).

Overthrust Belt

The chemical composition of the Salt Lake aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **appendix E–5**. The TDS concentrations (193 and 202 mg/L) indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Salt Lake aquifer in the OTB 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.

Star Valley
The chemical composition of the Salt Lake aquifer in Star Valley (SV) was characterized and the quality evaluated on the basis of environmental water samples from as many as 4 springs and 23 wells. Summary statistics calculated for available constituents are listed in **appendix E–6**, and major-ion composition in relation to TDS for wells completed in the aquifer is shown on a trilinear diagram (**appendix F–6, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–6; appendix F–6, diagram B**). TDS concentrations available for two of four springs were 236 and 287 mg/L. TDS concentrations for the wells ranged from 141 to 347 mg/L, with a median of 270 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from the Salt Lake aquifer in SV was suitable for all uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Concentrations of some properties and constituents in water from wells in the Salt Lake aquifer in the SV 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 (the 1 sample analyzed for this constituent exceeded the proposed MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L) and radium-226 plus radium-228 [1 of 3 samples exceeded the USEPA MCL of 5 pCi/L]. Concentrations of two constituents exceeded USEPA aesthetic standards for domestic use: iron (1 of 11 samples exceeded the SMCL of 300 µg/L) and manganese (1 of 11 samples exceeded the SMCL of 50 µg/L).

Concentrations of some characteristics and constituents in water from wells in the Salt Lake aquifer exceeded State of Wyoming standards for agricultural and livestock use in SV. Two constituents in environmental water samples from wells were measured at concentrations greater than agricultural-use standards: radium-226 plus radium-228 (1 of 3 samples exceeded the WDEQ Class II standard of 5 pCi/L) and iron (1 of 11 samples exceeded the WDEQ Class II standard of 5,000 µg/L). The concentration of one constituent (radium-226 plus radium-228) exceeded the livestock-use standard (1 of 3 samples exceeded the WDEQ Class III standard of 5 pCi/L).

7.2.4.4 Miocene gravel deposits

The physical and chemical characteristics of Miocene gravel deposits in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

Unnamed gravel deposits of Miocene age ("Miocene gravel deposits") are composed of gray, unconsolidated gravel to poorly cemented conglomerate that underlies the Conant Creek Tuff on the northeast and east sides of Signal Mountain; clasts are composed primarily of rounded quartzite, Paleozoic and Mesozoic sedimentary rock fragments, and Tertiary andesite (Love, 1989; Love and others, 1992). The unnamed gravel deposits are estimated to be 1,000- to 1,200-ft thick and have been identified only on Signal Mountain (Love, 1989, p. C40; Love and others, 1992).

Chemical characteristics

The chemical characteristics of groundwater from Miocene gravel deposits in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of Miocene gravel deposits 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–3**).

Jackson Hole
The chemical composition of groundwater from

Miocene gravel deposits in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations for available constituents are listed in **appendix E–3**. The TDS concentration (102 mg/L) from the well sample indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for, the quality of water from Miocene gravel deposits in JH 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.

7.2.4.5 Camp Davis aquifer

The physical and chemical characteristics of the Camp Davis aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

Saturated and permeable parts of the Miocene Camp Davis Formation compose the Camp Davis aquifer in the Snake/Salt River Basin (**pls. 4, 5**) (Love and Christiansen, 1985). The Camp Davis Formation consists of conglomeratic lower and upper members separated by a middle member composed of lacustrine limestone, siltstone, and tuff (Love, 1956a,c; Olson and Schmitt, 1987, and references therein). Reported thickness of the Camp Davis Formation in the Overthrust Belt ranges from about 100 to 5,500 ft (Love, 1956a, b, c; Schroeder, 1973, 1974, 1976, 1987; Love and Love, 2000).

Hydrogeologic data describing the Camp Davis aquifer in the Snake/Salt River Basin, including spring-discharge and well-yield measurements are summarized on **plate 3**. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Camp Davis Formation might be a fair to good aquifer (**pls. 4** and **5**). The Camp Davis Formation was classified as a major aquifer by Ahern and others (1981) and as a marginal aquifer in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4** and **5**). Cox (1976, Sheet 1) speculated that conglomerate in the Camp Davis Formation might "yield a few tens of gallons per minute from conglomerate," larger than the two well yields (2 and 10 gal/min) inventoried for the formation as part of this study (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Camp Davis aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Camp Davis 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–3** and **E–5**).

Jackson Hole

The chemical composition of the Camp Davis aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs and one well. Individual constituents are listed in **appendix E–3**. Major-ion composition in relation to TDS for springs issuing from the Camp Davis aquifer is shown on a trilinear diagram (**appendix F–3, diagram F**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagram F**). TDS concentrations for the springs ranged from 252 to 292 mg/L, with a median of 288 mg/L. The TDS concentration for the well was 180 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from three springs issuing from the Camp Davis aquifer in JH was suitable for most uses. One constituent (aluminum) exceeded USEPA aesthetic standards for domestic use (1 of 2 samples above lower SMCL standard of 50 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming domestic, agriculture, or livestock water-quality standards.

Concentrations of some properties and

constituents in water from one well completed in the Camp Davis aquifer in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured at a concentration greater than a health-based standard (USEPA MCL of 4 mg/L) and one constituent (arsenic) was measured at a concentration equal to its health-based standard (USEPA MCL of 10 µg/L). Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: pH (exceeded the upper SMCL limit of 8.5) and fluoride (exceeded the SMCL of 2 mg/L). No characteristics or constituents in the well sample approached or exceeded applicable State of Wyoming standards for agricultural-use standards. One characteristic (pH) was measured at values that exceeded the livestock-use standard (upper WDEQ Class III standard of 8.5).

Overthrust Belt

The chemical composition of the Camp Davis aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **appendix E–5**. The TDS concentration (306 mg/L) from the well indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Camp Davis aquifer in the OTB 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.

7.2.4.6 Teewinot aquifer

The physical and chemical characteristics of the Teewinot aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

Saturated and permeable parts of the Miocene Teewinot Formation compose the Teewinot aquifer in the Snake/Salt River Basin (**pls. 4** and **5**). The Teewinot Formation consists of chalky white to light-gray, soft, porous limestone, claystone, and pumicite (Love, 1956a; Love and others, 1992). The upper part of the formation is very fossiliferous, thin-bedded claystone, marlstone, and tuff, and the lower two-thirds of the formation is composed primarily of nodular porous limestone in 100- to 200-ft thick beds interbedded with pumicite in 20- to 75-ft thick beds (Love, 1956a; Love and others, 1992). A 110-ft thick conglomerate composed of limestone, quartzite, and obsidian clasts is present in the middle part of the formation (Love, 1956a, b; Love and others, 1992). Reported thickness of the Teewinot Formation is as much as 6,000 ft or more (Love and others, 1992; Love and Reed, 2000, 2001a,b; Love, 2001a,b,c, 2003b).

The Wyoming Water Planning Program (1972, Table III-2) speculated that the Teewinot Formation might be a poor aquifer (**pls. 4** and **5**). The Teewinot Formation was classified as a major aquifer by Ahern and others (1981) and in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4** and **5**). Hydrogeologic data describing the Teewinot aquifer in the Snake/Salt River Basin, including spring-discharge and well-yield measurements, are summarized on **plate 3**. Cox (1976, Sheet 1) reported yields as much as 120 gal/min per well from fractures and solution channels in limestone in the formation. Yields of four wells completed in the Teewinot aquifer inventoried as part of this study were smaller than reported by Cox, ranging from 10 to 50 gal/min (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Teewinot aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Teewinot 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–3**).

Jackson Hole
The chemical composition of the Teewinot aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs and three wells. Individual constituents are listed in **appendix E–3**. Major-ion composition in relation to TDS for springs issuing from and wells completed in the Teewinot aquifer is shown on trilinear diagrams (**appendix F–3, diagrams G** and **H**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; appendix F–3, diagrams G** and **H**). The TDS concentrations for the springs ranged from 244 to 254 mg/L, with a median of 247 mg/L. The TDS concentration for the wells ranged from 166 to 260 mg/L, with a median of 212 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Teewinot aquifer in springs and wells in JH 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.

7.2.4.7 Colter Formation

The physical and chemical characteristics of the Colter Formation in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Miocene Colter Formation in the Snake/Salt River Basin (**pls. 5** and **6)** consists of pyroclastic conglomerate, sandstone, and claystone (Love, 1956a; Love and others, 1992). Reported thickness of the Colter Formation in the Jackson Hole area is as much as 7,000 ft (Love, 1956a; Love and others, 1992).

The Wyoming Water Planning Program (1972, Table III-2) speculated that the Colter Formation might be a fair to poor aquifer (**pls. 5** and **6**). Cox (1976, Sheet 1) speculated that the Colter Formation might yield a few gallons per minute per well. Few hydrogeologic data describing the Colter Formation in the Snake/Salt River Basin were inventoried as part of this study, but one available spring-discharge measurement (1 gal/min) is shown on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Colter Formation in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Colter Formation 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–3**).

Jackson Hole
The chemical composition of the Colter Formation in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–3**. The TDS concentration (114 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Colter Formation in one spring in JH 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.

7.2.4.8 White River aquifer

Saturated and permeable parts of the Oligocene White River Formation compose the White River aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The White River Formation consists of white nodular calcareous siltstone and pale-green bentonitic claystone that locally can contain vertebrate fossils (Love and others, 1992). Reported thickness of the White River Formation in the Overthrust Belt ranges from 0 to 200 ft (Lines and Glass, 1975, Sheet 1; Love and others, 1992; Love, 2002). Despite the predominant fine grain size of sediments composing the unit, the formation is tentatively classified as an aquifer herein (**pls. 5**

and **6**). The White River Formation generally is defined as an aquifer throughout Wyoming where permeable, including areas immediately east of the Snake/Salt River Basin in the Wind River and Bighorn Basins (**pls. 5** and **6**). Permeability in the predominantly fine-grained rocks composing the unit is provided primarily by local secondary permeability development (for example, fractures), and much less commonly occurring local coarse-grained zones (Bartos and others, 2012). In areas where secondary permeability or coarse-grained zones are not present, the formation is defined as a confining unit. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.9 Conglomerate of Sublette Range

The Eocene and Paleocene Conglomerate of Sublette Range of Love and others (1993) (**pl. 4**) [also called the Sublette Range Conglomerate (Salat and Steidtmann, 1991)] consists of white, pink, dark gray, well-rounded, poorly sorted, pebble to boulder gravel composed of quartzite and gray chert mixed with silt and sand (Love and Christiansen, 1985, Sheet 2; Salat, 1989; Salat and Steidtmann, 1991). Reported maximum thickness of the Conglomerate of Sublette Range is about 591 ft (Oriel and Platt, 1980). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.10 Wasatch aquifer (Overthrust Belt)

The Eocene Wasatch Formation comprises the Wasatch aquifer within the Overthrust Belt part of the Snake/Salt River Basin (**pl. 4**). The Wasatch aquifer is undeveloped as a water supply within the Snake/Salt River Basin study boundary within the Overthrust Belt. However, immediately south in the Bear River Basin within the Overthrust Belt, the aquifer is used as a source of water for domestic, stock, industrial, and public-supply purposes (Bartos and others, 2014). Characteristics of the Wasatch aquifer in the Snake/Salt River Basin likely are similar to those in the Bear River Basin.

The Wasatch Formation consists of variegated mudstone, claystone, siltstone, shale, sandstone, conglomeratic sandstone, and conglomerate. It is a thick sequence of nonmarine sedimentary rock with named members of the formation (described below but individual members not shown on **plate 4**) in some areas of the Overthrust Belt.

The Wasatch Formation in the Overthrust Belt (including the Snake/Salt River Basin) is divided into a basal conglomerate, a lower unnamed member, the main body of the formation, and the Bullpen and Tunp Members (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993) (individual members not shown on Plate 4). The basal conglomerate is a lenticular conglomerate of sandstone pebbles and cobbles, and ranges from 0 to 300 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; M'Gonigle and Dover, 1992). The lower unnamed member is composed predominantly of drab-colored mudstone and sandstone, and ranges from 0 to 300 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; M'Gonigle and Dover, 1992). The main body is composed predominantly of red, purple, and tan mudstone, with some sandstone, and ranges from 1,500 to 2,000 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Bullpen Member is composed predominantly of red and salmon mudstone, and gray and brown mudstone, and ranges from 0 to 400 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; M'Gonigle and Dover, 1992). The Tunp Member is composed of conglomeratic mudstone and diamictite, and ranges from 200 to 500 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; Hurst, 1984; Hurst and Steidtmann, 1986; M'Gonigle and Dover, 1992).

The Wasatch Formation is considered to be an aquifer in the Overthrust Belt by previous investigators (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern and others, 1981; Forsgren Associates, 2000; TriHydro Corporation, 2000, 2003) (**pl. 4**). In the Wyoming Water Framework Plan, the Wasatch Formation is classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**). The Wasatch aquifer is an important aquifer in the adjacent Green River Basin to the east (Ahern and others, 1981; Martin, 1996; Naftz, 1996; Glover and others, 1998; Bartos and Hallberg, 2010). Ahern and others (1981, Figure II-7) classified the formation as a major aquifer in the Overthrust Belt (**pl. 4**) and noted that both springs issuing from and wells completed in the formation locally yielded water. The Wasatch Formation has been defined as a "productive aquifer" in the Deer Mountain Subdivision area near the town of Bear River in the Bear River Basin located immediately south of the Snake/Salt River Basin (Forsgren Associates, 2000; TriHydro Corporation, 2000).

Although little information was available at the time of their studies, previous investigators speculated that small to moderate yields sufficient for domestic and stock use were likely from permeable beds in the Wasatch Formation in the Overthrust Belt (Berry, 1955; Robinove and Berry, 1963; Wyoming Water Planning Program, 1972, Table III-2). Lines and Glass (1975, Sheet 1) noted that conglomeratic sandstones and conglomerates in the Wasatch Formation likely were capable of yielding "moderate to large quantities" of water to wells. In addition, the investigators (Lines and Glass, 1975, Sheet 1) noted that fine-grained sandstones in the Wasatch Formation were capable of yielding "small to moderate" quantities of water, but that well yields were likely "greatly dependent" on the saturated thickness of the sandstone beds. Similarly, Ahern and others (1981) noted that permeable sandstones, conglomeratic sandstones, and conglomerates of the Wasatch Formation could yield moderate to large quantities of water to wells. Sandstones, conglomeratic sandstones, and conglomerates composing the Wasatch aquifer primarily are under confined conditions, except in outcrop areas where unconfined (water-table) conditions are present. Although no data were located describing the physical and chemical characteristics of the hydrogeologic unit within the boundary of the Snake/Salt River Basin, Wasatch aquifer characteristics in the Bear River Basin to the south and within the Overthrust Belt are provided in Bartos and others (2014).

7.2.4.11 Wasatch-Fort Union aquifer (Green River and Hoback Basins)

The physical and chemical characteristics of the Wasatch-Fort Union aquifer in the Green River and Hoback Basins within the Snake/Salt River Basin are described in this section of the report. The Wasatch-Fort Union aquifer is composed of two zones represented by the Wasatch and Fort Union Formations and related formations such as the Pass Peak and Hoback Formations (Bartos and Hallberg, 2010, Figure 5-1, and references therein). The aquifer forms the base of the lower Tertiary aquifer system in the Green River Basin, and is in direct contact with underlying Upper Cretaceous rocks at the top of the Mesaverde aquifer (Bartos and Hallberg, 2010, Figure 5-1). No regional confining unit separates the lower Tertiary aquifer system in the Green River Basin from the underlying Mesaverde aquifer. The Wasatch-Fort Union aquifer is the thickest Cenozoic hydrogeologic unit in the Green River Basin, as much as 11,000-ft thick.

Physical characteristics

The physical characteristics of the Wasatch and Fort Union zones of the Wasatch-Fort Union aquifer in the Green River and Hoback Basins within the Snake/Salt River Basin are described in this section of the report.

7.2.4.12 Wasatch Zone of the Wasatch-Fort Union aquifer (including Pass Peak Formation)

The Wasatch zone of the Wasatch-Fort Union aquifer is composed of the Wasatch Formation (main body), undifferentiated Green River and Wasatch Formations along the western edge of the Green River Basin, the Pass Peak Formation in the

northwestern Green River Basin, various Eocene (and possibly younger) rocks in the northeastern Green River Basin, as well as numerous small tongues and members including the Farson Sandstone Member of the Green River Formation and the Alkali Creek Member of the Wasatch Formation between the New Fork River and the southernmost exposure of the Laney aquifer in the north and central Green River Basin; the Niland Tongue of the Wasatch Formation in the southeast Green River Basin; the "La Barge Member"; the Chappo Member of the Wasatch Formation; and the Luman Tongue of the Green River Formation in the southeast Green River Basin (Martin, 1996; Glover and others, 1998; Bartos and Hallberg, 2010, and references therein). The Eocene Pass Peak Formation consists of conglomerate, sandstone, and shale; thickness is as much as 5,000 ft (Welder, 1968, Sheet 2; Cox, 1976, Sheet 1).

Sandstone beds, interbedded with various fine-grained sedimentary rocks in these various units composing the Wasatch zone, generally provide most of the water to wells completed in the aquifer. The thickness and amount of sandstone at a given location generally depends on the distance from the sediment source area. Throughout the northern Green River Basin, many investigators have noted thick, permeable, areally extensive sandstones at or near land surface. In fact, Welder (1968, sheet 2) noted that "aggregate thickness of water-bearing sandstone probably ranges from one-third to two-thirds of total formation thickness; consequently, a large amount of water is in storage and the water is under pressure where deeply buried." In the southern Green River Basin, the Wasatch zone is overlain by the Green River Formation, and the number and thickness of sandstone beds in the aquifer varies greatly both laterally and vertically. Large well yields in thick sandstone have been reported along basin margins. Welder (1968, Sheet 2) speculated that groundwater-development possibilities were "good" in the Green River Basin. Cox (1976, Sheet 1) speculated that conglomerate and sandstone in the Pass Peak Formation might "yield a few tens of gallons per minute per well," larger than the two well yields (2 and 5 gal/min) inventoried for the formation as part of this study (**pl. 3**).

Groundwater in the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin generally flows from basin margins (assumed to represent recharge areas) toward the center of the basin and to the south (assumed to represent discharge areas) (Martin, 1996). Water-table conditions in the aquifer predominate in the northern Green River Basin, whereas artesian (confined) conditions predominate elsewhere.

7.2.4.13 Fort Union Zone of the Wasatch-Fort Union aquifer (including the Hoback Formation)

The Fort Union zone of the Wasatch-Fort Union aquifer is composed of the Fort Union Formation and the Hoback Formation (Martin, 1996; Glover and others, 1998; Bartos and Hallberg, 2010, and references therein). The Hoback Formation is equivalent to the Fort Union Formation in the northwestern Green River Basin. The Fort Union Formation is lithologically very similar to the Wasatch Formation; it is also composed of fluvial sandstones and fine-grained sedimentary rocks. In the subsurface, it is often difficult to differentiate the two formations. The Hoback Formation is composed of gray and brown sandstone, conglomerate, shale, siltstone, and shaley limestone; maximum thickness is about 16,000 ft, but the formation thins southward in its outcrop area to about 8,000 ft (Spearing, 1969, Figure 4; Lines and Glass, 1975, Sheet 1; Cox, 1976, Sheet 1). Although the Fort Union zone is present throughout the Green River Basin, Martin (1996, p. 21) noted that the "northwestern part of the [Green River] structural basin where the Hoback Formation is exposed at the surface, the Fort Union zone is not included as part of the aquifer system because it is north of a groundwater divide outside of the hydrologic basin."

Few hydrologic data are available for the Hoback Formation in the Snake/Salt River Basin (**pl. 3**), but because of large thicknesses of sandstone and conglomerate, it is considered a potential source of water (Lines and Glass, 1975, Sheet 1). Cox (1976, Sheet 1) speculated that sandstone in the Hoback Formation might "yield a few tens of gallons per minute per well," similar to the one well yield (20

gal/min) inventoried for the formation as part of this study (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Wasatch-Fort Union aquifer (samples collected from the Pass Peak and Hoback Formations) in the Snake/Salt River Basin, are described in this section of the report. Groundwater quality from both the Pass Peak and Hoback Formations 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–4**).

Green River and Hoback Basins
The chemical composition of the Wasatch-Fort Union aquifer (samples collected from the Pass Peak Formation) in the Green River and Hoback Basins (GH) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **appendix E–4**. TDS concentrations (283 and 367 mg/L) indicated that waters from both springs were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Wasatch-Fort Union aquifer (Pass Peak Formation) in the GH 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.

The chemical composition of the Wasatch-Fort Union aquifer (samples collected from the Hoback Formation) in the GH was characterized and the quality evaluated on the basis of environmental water samples from one spring and two wells. Individual constituent concentrations are listed in **appendix E–4**. TDS concentrations for the spring (275 mg/L) and for the wells (215 and 327 mg/L) indicated waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4**). One constituent (mercury) measured in the spring sample was greater than the State of Wyoming agricultural-use standard (WDEQ Class II standard of 0.05 µg/L). No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic or livestock water-quality standards in the spring sample. On the basis of the characteristics and constituents analyzed for, the quality of water from the two wells completed in the Wasatch-Fort Union aquifer (Hoback Formation) in the GH was suitable for most uses. No characteristics or constituents measured in the two well samples approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in environmental samples from wells.

7.2.4.14 Tepee Trail Formation

The Eocene Tepee Trail Formation in the Snake/Salt River Basin (**pls. 5** and **6)** consists of tuffaceous sandstone, mudstone, and claystone (Love, 1956a; Love and others, 1992). Reported thickness of the Tepee Trail Formation in the Jackson Hole area is as much as 1,500 ft (Love and Keefer, 1972). For the Wind River Basin, Bartos and others (2012, Plate 2) assigned the Tepee Trail Formation to part of a confining unit identified as the "Aycross-Wagon Bed confining unit" (**pls. 5** and **6**) composed of the volcaniclastic Eocene Tepee Trail and Aycross Formations or siliciclastic Wagon Bed Formation. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.15 Hominy Peak Formation

The Eocene Hominy Peak Formation in the Snake/Salt River Basin (**pls. 5** and **6)** consists of mafic volcaniclastic conglomerate, tuff with sparse claystone in the upper part of the formation, and gold-bearing conglomerate at the base of the formation (Love and others, 1978). The formation is exposed at the north end and on the west flank of the Teton Range and the south boundary of Yellowstone National Park (**pl. 1**). Love and others (1978) assigned the formation to the Absaroka Volcanic Supergroup of Smedes and Prostka (1972). Reported thickness of the Hominy

Peak Formation is as much as 2,000 ft (Love and others, 1978). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.16 Aycross Formation

The Eocene Aycross Formation in the Snake/Salt River Basin (**pls. 5** and **6**) consists of tuffaceous sandstone, mudstone, and claystone (Love, 1956a; Love and others, 1992). Reported thickness of the Aycross Formation in the Jackson Hole area is as much as 1,500 ft (Love, 1956a; Rohrer and Obradovich, 1969). In the Wind River Basin, Bartos and others (2012, Plate 2) assigned the Aycross Formation to part of a confining unit identified as the "Aycross-Wagon Bed confining unit" (**pls. 5** and **6**) composed of the volcaniclastic Eocene Tepee Trail and Aycross Formations or siliciclastic Wagon Bed Formation. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.17 Crandall Conglomerate

The Eocene Crandall Conglomerate (**pl. 6**) is a clast-supported conglomerate composed of locally derived Paleozoic carbonate clasts (Love and Christiansen, 1985; Breeden and others, 2012). Thickness of the formation is as much as 328 ft (Breeden and others, 2012). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.2.4.18 Wind River aquifer

Present within a small part of the east-central Snake/Salt River Basin study area (**pls. 1** and **2)**, the Wind River aquifer consists of the Eocene Wind River Formation (**pls. 5** and **6**) (Bartos and others, 2012, and references therein). Thickness of the Wind River Formation in the Wind River Basin ranges from about 100 ft along mountain flanks to about 5,000 ft in the central part of the Wind River Basin (Bartos and others, 2012, and references therein). 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 and others, 1959; McGreevy and others, 1969; Richter, 1981). Coarser deposits may be more abundant along the basin margins because of proximity to sediment sources such as the Washakie Range and Wind River Mountains (Whitcomb and Lowry, 1968).

In the Wind River Basin, 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 and others, 2012, Plate II). In the Wind River Mountains, the Wind River Formation may be underlain by the Conglomerate of Roaring Fork (Bartos and others, 2012, Plate II). Where buried in the Wind River Basin, 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 and others, 2012, Plate II)], or Quaternary unconsolidated deposits (Bartos and others, 2012, Plate II).

The Wind River aquifer is used as a source of water for domestic, stock, irrigation, industrial, and public-supply purposes throughout the Wind River Basin (Richter, 1981; Bartos and others, 2012). Many wells are installed in the Wind River aquifer in the Wind River Basin because it is present at or near land surface (crops out) throughout most of the basin. 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 and others, 1959; Whitcomb and Lowry, 1968; McGreevy and others, 1969; Richter, 1981; Bartos and others, 2012). Because of limited areal extent and location away from any population, the aquifer is unused in the Snake/Salt River Basin. No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Snake/Salt River Basin.

7.2.4.19 Devils Basin Formation

The Paleocene Devils Basin Formation (**pl. 5**) consists of gray, soft, lenticular, poorly bedded sandstones; bedded gray and pale-green siltstones and claystones; thin-bedded brown to black carbonaceous shale; and thin beds of coal (Love, 1989). Thickness of the type section is about 1,500 ft (Love, 1989). No data were located describing the physical and chemical hydrogeologic characteristics of the Devils Basin Formation in the Snake/Salt River Basin.

7.2.4.20 Pinyon Conglomerate

The Upper Cretaceous to Paleocene Pinyon Conglomerate (**pls. 5** and **6**) consists of rusty-brown conglomerate composed of quartzite cobbles and pebbles in a matrix of rusty coarse-grained sandstone and occasional boulders of older conglomerate and quartzite (Lindsey, 1972; Love and others, 1992). The formation is as much as 3,800-ft thick in the Snake/Salt River Basin (Lindsey, 1972; Love, 1974a,b, 2001c, 2003b; Love and others, 1992). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Pinyon Conglomerate might be a "fair to poor aquifer." Cox (1976, Sheet 1) speculated that wells completed in the formation might yield a few tens of gallons per minute per well. No data were located describing the physical and chemical hydrogeologic characteristics of the Pinyon Conglomerate in the Snake/Salt River Basin.

7.3 Mesozoic hydrogeologic units

Mesozoic hydrogeologic units (aquifers and confining units) are described in this section of the report. Lithostratigraphic units of Cretaceous, Jurassic, and Triassic age compose the Mesozoic hydrogeologic units (aquifers and confining units) in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Depending on location and depth, wells completed in Mesozoic hydrogeologic units produce highly variable quantities and quality of water. The highly complex structural features of the Overthrust Belt require site-specific geologic and hydrogeologic investigation to characterize and develop groundwater resources from Mesozoic hydrogeologic units.

Development of most Mesozoic aquifers in the Snake/Salt River Basin has been very limited to date (2014), except in areas where aquifers crop out and are directly exposed at land surface or at shallow depth below younger hydrogeologic units. Hydraulic properties, great depth, minimal precipitation and recharge, and generally poor water quality except near recharge areas prevents extensive groundwater development of aquifers in Mesozoic hydrogeologic units.

7.3.1 Landslide Creek Formation

The Upper Cretaceous Landslide Creek Formation (**pl. 6**) consists of greenish-gray, bentonitic, tuffaceous sandstone and conglomerate (Love and Christiansen, 1985). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Landslide Creek Formation might be a poor aquifer (**pl. 6**). No data were located describing the physical and chemical hydrogeologic characteristics of the Landslide Creek Formation in the Snake/Salt River Basin.

7.3.2 Harebell Formation

The physical and chemical characteristics of the Harebell Formation in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Upper Cretaceous Harebell Formation (**pls. 5** and **6**) consists of sandstone, shale, conglomerate, sandstone, claystone, and tuff (Love, 1956a; Lindsey, 1972; Love and others, 1992). The conglomerate consists of quartzite roundstones in a matrix of brown, gold-bearing sandstone. The sandstone is brown, gray, dull green, silty, hard, and tuffaceous. The claystone is gray, dark green, black, and mustard yellow, silty, and tuffaceous. Reported maximum thickness of the Harebell Formation ranges from 5,000 to 10,000 ft (Love, 1974a,b, 1975a,b, 2002; Love and others, 1992).

Few hydrogeologic data are available describing the hydrogeologic characteristics of the Harebell

Formation in the Snake/Salt River Basin. Hydrogeologic data describing the physical characteristics of the Harebell Formation, including well-yield measurements and other hydraulic properties, are summarized on **plate 3**. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Harebell Formation might be a good aquifer (**pls. 5** and **6**). The Harebell Formation was classified as a marginal aquifer in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Cox (1976, Sheet 1) speculated that the Harebell Formation might yield a few tens of gallons per minute per well from conglomerate and sandstone. Yields of two wells completed in the Harebell Formation inventoried as part of this study (12 and 20 gal/min) were similar to those speculated by Cox (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Harebell Formation in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Harebell Formation 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–3**).

Jackson Hole

The chemical composition of the Harebell Formation in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from one spring and two wells. Individual constituents are listed in **appendix E–3**. TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**). The TDS concentration for the spring was 278 mg/L. The TDS concentrations for the wells were 280 and 314 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from the Harebell Formation in the spring in JH 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.

Concentrations of some properties and constituents in water from wells completed in the Harebell Formation 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 (fluoride) exceeded health-based standards (1 of 2 samples exceeded the USEPA MCL of 4 mg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: pH (1 of 2 samples exceeded the upper SMCL limit of 8.5) and fluoride (1 of 2 samples exceeded the SMCL of 2 mg/L).

Concentrations of some characteristics and constituents in water from wells completed in the Harebell Formation exceeded State of Wyoming standards for agricultural and livestock use in JH. Two characteristics in the wells approached or exceeded applicable State of Wyoming standards for agricultural-use standards: pH (1 of 2 samples exceeded upper WDEQ Class II standard of 9) and SAR (1 of 2 samples exceeded WDEQ Class II standard of 8). The value of one characteristic (pH) exceeded the livestock-use standard (1 of 2 samples exceeded upper WDEQ Class III standard of 8.5).

7.3.3 Meeteetse Formation

The Upper Cretaceous Meeteetse Formation (**pl. 5**) consists of chalky-white to gray salt-and-pepper soft sandstone, interbedded with yellow, pale green, and dark-gray carbonaceous shale, thin coal beds, white slabby tuff, and yellow to gray bentonite beds (Love and others, 1992). Conglomerate in the formation consists of quartzite cobbles that can be in a gold-bearing sandstone matrix in some horizons. Maximum thickness of the formation ranges from about 500 to 1,000 ft (Cox, 1976, Sheet 1; Love, 1975a, 2002, 2003b; Love and others, 1992).

Few hydrogeologic data are available describing

the hydrogeologic characteristics of the Meeteetse Formation in the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Meeteetse Formation might be a poor aquifer in the Snake/Salt River Basin (**pl. 5**). The Meeteetse Formation was classified as a major aquitard in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pl. 5**). Cox (1976, Sheet 1) speculated that the Meeteetse Formation might yield a few tens of gallons per minute per well from sandstone. No data were located describing the physical and chemical hydrogeologic characteristics of the hydrogeologic unit in the Snake/Salt River Basin.

7.3.4 Mesaverde aquifer

Saturated and permeable parts of the Upper Cretaceous Mesaverde Formation compose the Mesaverde aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The Mesaverde Formation (**pls. 5** and **6)** consists of white massive to thick-bedded, soft, porous, medium- to coarse-grained sandstone interbedded with thin gray shale and sparse coal and bentonite beds (Love and others, 1992). Conglomerate beds containing quartzite cobbles in a gold-bearing matrix occur locally in the Grand Teton National Park area. Maximum thickness of the formation ranges from about 800 to 1,200 ft or more (Rohrer, 1969; Cox, 1976, Sheet 1; Love, 1975a, 2002, 2003b; Love and others, 1992).

Few hydrogeologic data are available describing the hydrogeologic characteristics of the Mesaverde Formation in the Snake/Salt River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from adjacent structural basins. The Mesaverde Formation generally is defined as an aquifer throughout Wyoming, including the Overthrust Belt and in areas immediately east of the Snake/Salt River Basin in the Wind River and Bighorn Basins, and southeast in the Green River Basin (**pls. 5** and **6**); consequently, the Mesaverde Formation in the Snake/Salt River Basin was classified as an aquifer herein (**pls. 5** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Mesaverde Formation might be a poor aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). Ahern and others (1981) classified the Mesaverde Formation as an aquifer in the Overthrust Belt. The Mesaverde Formation was classified as a minor aquifer in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Cox (1976, Sheet 1) speculated that the Mesaverde Formation might yield a few tens of gallons per minute per well from sandstone. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.5 Everts Formation, Eagle Sandstone, and Telegraph Creek Formation

The Upper Cretaceous Everts Formation, Eagle Sandstone, and Telegraph Creek Formation (**pl. 6)** consist of massive to thin-bedded sandstone, mudstone, and shale (Love and Christiansen, 1985, Sheet 2). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Everts Formation might be a fair to poor (?) aquifer, the Eagle Sandstone was probably a fair aquifer, and the Telegraph Creek Formation might be a fair to poor aquifer in the Snake/Salt River Basin (**pl. 6**). Cox (1976, Sheet 1) speculated that sandstone in the formations might yield a few tens of gallons per minute per well. No data were located describing the physical and chemical hydrogeologic characteristics of the three lithostratigraphic units in the Snake/Salt River Basin.

7.3.6 Sohare Formation

The physical and chemical characteristics of the Sohare Formation in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Upper Cretaceous Sohare Formation (**pls. 5** and **6)** consists of lenticular gray and brown fine-

grained sandstone interbedded with light- and dark-gray shale and siltstone with thin coal beds (Love, 1989; Love and others, 1992). The Sohare Formation is exposed in broad outcrops along the east side of Jackson Hole and is present on both flanks of the Gros Ventre Range to the south (**pl. 1**). Thickness varies from about 5,000 ft south of the Gros Ventre Range to an eroded edge just south of Yellowstone National Park (Love, 1989).

Few data are available describing the hydrogeologic characteristics of the Sohare Formation in the Snake/Salt River Basin. The Sohare Formation was classified as a marginal aquifer in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). No data were located describing the physical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

Chemical characteristics

The chemical characteristics of groundwater from the Sohare Formation in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Sohare Formation 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 as quantile values (**appendix E–3**).

Jackson Hole
The chemical composition of groundwater from the Sohare Formation in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituents are listed in **appendix E–3**. The TDS concentration (866 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–3**).

Concentrations of some properties and constituents in water from the well completed in the Sohare Formation in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards, but one characteristic (TDS) exceeded USEPA aesthetic standards for domestic use (exceeded SMCL limit of 500 mg/L). One characteristic (SAR) exceeded the applicable State of Wyoming standard for agricultural use (exceeded WDEQ Class II standard of 8). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.3.7 Blind Bull Formation

The physical and chemical characteristics of the Blind Bull Formation in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Upper Cretaceous Blind Bull Formation (**pl. 4**) is present in the Snake/Salt River Basin. The Blind Bull Formation consists of partly conglomeratic sandstone, siltstone, claystone, coal, and bentonite (Rubey, 1973b; Oriel and Platt, 1980; Rubey and others, 1980). The Blind Bull Formation is a lateral stratigraphic equivalent to part of the Sohare Formation and Bacon Ridge Sandstone in the northern part of the Snake/Salt River Basin, and to part of the Hilliard Shale in the southern part of the Overthrust Belt, south of the Snake/Salt River Basin. The Hilliard Shale is located in the eastern and southern parts of the Overthrust Belt, and this shale unit becomes increasingly sandy northward and northwestward as it laterally grades into the Blind Bull Formation (Rubey, 1973b; Oriel and Platt, 1980; Rubey and others, 1980). Maximum thickness of the Blind Bull Formation in the Overthrust Belt ranges from 5,000 ft to as much as 9,186 ft (Rubey, 1973b; Schroeder, 1979, 1987; Oriel and Platt, 1980; Rubey and others, 1980).

Few data are available describing the hydrogeologic characteristics of the Blind Bull Formation in the Snake/Salt River Basin. Lines and Glass (1975, Sheet 1) speculated that sandstone in the Blind Bull Formation might be able to produce "small quantities of water." Two spring-discharge measurements for the formation (20 and 25 gal/min) were inventoried as part of this study (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Blind Bull Formation in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Blind Bull Formation 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–5**).

Overthrust Belt
The chemical composition of groundwater from the Blind Bull Formation in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations for available constituents are listed in **appendix E–5**. The TDS concentration (172 mg/L) from the spring indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Blind Bull Formation in the OTB 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.

7.3.8 Bacon Ridge aquifer

The physical and chemical characteristics of the Bacon Ridge aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

Saturated and permeable parts of the Upper Cretaceous Bacon Ridge Sandstone comprise the Bacon Ridge aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The Bacon Ridge Sandstone in the Grand Teton National Park area consists of tan to gray, thick-bedded, fine-grained sandstone containing abundant marine fossils interbedded with gray marine and brackish-water shale and siltstone (Love and others, 1992). Thin bentonite beds occur near the top and lower parts of the formation, and coal beds occur in parts of the formation. A 30-ft thick gold-bearing quartzite boulder conglomerate is present in the lower part of the formation and intertongues with marine strata. Reported maximum thickness of the Bacon Ridge Formation ranges from 1,000 to 1,500 ft (Love and others, 1992).

Few hydrogeologic data are available describing the hydrogeologic characteristics of the Bacon Ridge aquifer in the Snake/Salt River Basin. Hydrogeologic data describing the physical characteristics of the Bacon Ridge aquifer, including spring-discharge and well-yield measurements, are summarized on **plate 3**. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Bacon Ridge Formation might be a good aquifer (**pls. 5** and **6**). The Bacon Ridge Formation was classified as a marginal aquifer in the Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Cox (1976, Sheet 1) speculated that the Bacon Ridge Formation might yield a few tens of gallons per minute per well from sandstone.

Chemical characteristics

The chemical characteristics of groundwater from the Bacon Ridge aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Bacon Ridge 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–3**).

Jackson Hole
The chemical composition of the Bacon Ridge aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from one spring and one well. Individual constituents are listed in **appendix E–3**. TDS concentrations (216 mg/L in the spring sample and 547 mg/L in the well sample) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**).

On the basis of the characteristics and constituents analyzed for, the quality of water from the spring issuing from the Bacon Ridge aquifer in JH was suitable for all uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Concentrations of some properties and constituents in water from the well completed in the Bacon Ridge aquifer in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards. Two characteristics exceeded USEPA aesthetic standards for domestic use: pH (value greater than the upper SMCL limit of 8.5) and TDS (concentration greater than SMCL of 500 mg/L). Two characteristics exceeded applicable State of Wyoming standards for agricultural-use standards: pH (value greater than upper WDEQ Class II standard of 9) and SAR (value exceeded WDEQ Class II standard of 8). The value of one characteristic (pH) exceeded a livestock-use standard (value exceeded upper WDEQ Class III standard of 8.5).

7.3.9 Cody confining unit

The Cody confining unit is composed of the Upper Cretaceous Cody Shale (**pls. 5** and **6**). Deposited in a marine environment, the Cody Shale consists of dull-gray shale interbedded with lesser amounts of gray siltstone and gray fine-grained slabby glauconitic sandstone (Love and others, 1992). Thickness of the Cody Shale ranges from 1,400 to 2,200 ft in the Jackson Hole area, 1,000 to 2,000 ft in the Green River and Hoback Basins, and 1,000 to 2,000 ft in the Gros Ventre Range (Love and others, 1992; Love and Love, 2000; Love, 2003a).

Because the lithostratigraphic unit is composed primarily of shale, the Cody Shale was classified as a confining unit by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein), and throughout the State in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Cody Shale are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as a confining unit was retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Despite being classified as a confining unit, the Cody confining unit likely can yield water locally in areas where discontinuous sandstone beds or zones with fractures (secondary permeability) are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Cox, 1976, Sheet 1). Cox (1976, Sheet 1) speculated that the sandstone beds probably would not yield more than a few gallons per minute per well. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.10 Frontier aquifer

The physical and chemical characteristics of the Frontier aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Frontier aquifer is composed of the Upper Cretaceous Frontier Formation (**pls. 4, 5,** and **6**). The Frontier Formation consists of interbedded white to brown fine- to medium-grained sandstone and dark gray shale with beds of abundant oyster fossils in the upper part of the formation (Oyster Ridge Sandstone Member), and coal and lignite beds in the lower part (individual members not shown on **plates. 4, 5,** and **6**). The Frontier Formation is not exposed above and to the west of the Absaroka thrust fault (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993) (**pl. 1**), where the Upper Cretaceous lower member of the Evanston Formation unconformably overlies the Lower Cretaceous Sage Junction Formation. The Frontier Formation was divided into additional members by Hale (1960), including the Dry Hollow, Allen Hollow Shale, Coalville, and Chalk Creek Members.

Frontier Formation thickness in the Snake/Salt River Basin varies by geographic area in the Snake/Salt River Basin. Thickness of the Frontier Formation ranges from 1,200 to 3,000 ft in the Overthrust Belt, 1,000 to 2,000 ft in the Northern Ranges, and is about 1,000 ft in Jackson Hole (Jobin, 1965; Love, 1974a, 1975b, 2001c, 2003a; Schroeder, 1974; Christiansen and others, 1978; Oriel and Platt, 1980; Rubey and others, 1980; Ahern and others, 1981; Oriel and Moore, 1985; Love and others, 1992; Love and Love 2000).

Previous investigators have classified the Frontier Formation as an aquifer and that definition is retained herein (**plates 4** and **5**). Robinove and Berry (1963, Plate 1) speculated that the Frontier Formation in the Bear River valley in the Overthrust Belt south of the Snake/Salt River Basin was "possibly an aquifer in areas." Lines and Glass (1975, Sheet 1) noted that sandstone aquifers in the Frontier Formation were capable of yielding moderate quantities of water and were the "best aquifers" in their "hydrogeologic division 5" (identified as being composed of Cretaceous shales and sandstones and shown on **plates 4, 5,** and **6**) in the Overthrust Belt. Similarly, the Frontier Formation was classified as a minor aquifer yielding moderate quantities of water by Ahern and others (1981, Figure II-7, and Table IV-1) in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). North of the Overthrust Belt, Cox (1976, Sheet 1) speculated that the Frontier Formation might yield a few tens of gallons per minute per well from sandstone; in addition, he noted that springs issuing from the formation in the Gros Ventre Range yield "a few gallons per minute." In the Wyoming Water Framework Plan, the Frontier Formation was classified as a minor aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5**, and **6**). All the investigators concluded that interbedded discontinuous sandstone beds compose the aquifer (Ahern and others, 1981; Lines and Glass, 1975, Sheet 1). Because sandstone beds compose the aquifer, permeability is primarily intergranular and related to the amount of cementation, except where fractured (Ahern and others, 1981). Hydrogeologic data (well yields) inventoried for the Frontier aquifer are shown on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Frontier aquifer in the Snake/Salt River Basin are described in this section of the report. 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 (**appendix E–2**).

Northern Ranges

The chemical composition of the Frontier aquifer in the Northern Ranges (NR) 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 E–2**. TDS concentrations indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2**). Major-ion composition in relation to TDS for the three springs issuing from the Frontier aquifer is shown on a trilinear diagram (**appendix F–2, diagram D**). The TDS concentrations for the springs ranged from 80 to 416 mg/L, with a median concentration of 338 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Frontier aquifer in the NR was suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA and State of Wyoming domestic, agricultural, or livestock water-quality standards.

7.3.11 Mowry confining unit

The Mowry confining unit is composed of the Upper Cretaceous Mowry Shale (**pls. 5** and **6**). The Mowry Shale consists of dark gray to black (weathers silvery gray), very hard, brittle, silicified, thin-bedded shale with some bentonite and secondarily silicified fine-grained sandstone (Love and others, 1992). Thickness of the Mowry Shale in the Gros Ventre Range ranges from 500 to 700 ft (Love, 1974a, 2001c; Love and Love, 1978, 2000; Love and others, 1992). Thickness of the Mowry Shale in Jackson Hole is about 650 ft

(Love, 2003a).

Because of the predominance of fine-grained lithologies such as shale, the Mowry Shale was classified as a confining unit by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein), and throughout the State in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Mowry Shale are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as a confining unit was retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Despite being classified as a confining unit, the Mowry confining unit likely can yield water locally in areas where discontinuous sandstone beds or zones with fractures (secondary permeability) are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Cox, 1976, Sheet 1). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.12 Aspen confining unit

The physical and chemical characteristics of the Aspen confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Aspen confining unit is composed of the Upper and Lower Cretaceous Aspen Shale (**pl. 4**). The Aspen Shale consists of interbedded light to dark gray shale, siltstone, and claystone with minor quartz-rich sandstone and porcellanite. Maximum thickness of the Aspen Shale in the Overthrust Belt ranges from less than 1,000 to 5,000 ft or more (Jobin, 1965, 1972; Pampeyan and others, 1967; Albee, 1968, 1973; Schroeder, 1969, 1973, 1974, 1976, 1979, 1987; Oriel and Platt, 1980; Schroeder and others, 1981; Oriel and Moore, 1985; Lageson, 1986). Maximum thickness of the Aspen Shale in the Teton Range is about 2,000 ft (Oriel and Moore, 1985). The Aspen Shale is laterally equivalent to the Mowry Shale (see **pls. 5** and **6**). Some beds are present that are transitional from the Aspen Shale to the lower part of the Blind Bull Formation (Rubey and others, 1980).

The Aspen Shale was identified as either "discontinuous aquifers with local confining beds" or a "locally utilized aquifer" in the Overthrust Belt by Ahern and others (1981, Figure II-7, and Table IV-1) (**pl. 4**). The investigators (Ahern and others, 1981, p. 61) also noted that the formation was composed primarily of low-permeability shale, and that "exploitable water yields were mainly from stray sands and fracture zones." In the Wyoming Water Framework Plan, the Aspen Shale was classified as a major aquitard (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**). Because shale is the predominant lithology, the Aspen Shale is classified as a confining unit herein (**pl. 4**); however, it is recognized that water can be obtained locally from the Aspen confining unit in areas where discontinuous sandstone beds or zones with fractures are present (Lines and Glass, 1975, Sheet 1; Ahern and others, 1981; Richter, 1981, Table IV-1). Lines and Glass (1975, Sheets 1, 2) noted that some domestic wells completed in permeable parts of the Aspen confining unit along the Snake River were abandoned because of hydrogen sulfide gas. Hydrogeologic data describing the Aspen confining unit in the Snake/Salt River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Aspen confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Aspen 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–3 and E–5**).

Jackson Hole
The chemical composition of the Aspen confining unit in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituents are listed in **appendix E–3**. TDS concentrations measured in water from the wells (284 and 312 mg/L) indicated that both waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**).

Concentrations of some properties and constituents in water from the Aspen confining unit in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The concentration of one constituent (fluoride) exceeded health-based standards (1 of 2 samples exceeded the USEPA MCL of 4 mg/L). Concentrations of two constituents exceeded USEPA aesthetic standards for domestic use: iron (1 of 2 samples exceeded SMCL of 300 µg/L) and fluoride (1 of 2 samples exceeded the SMCL of 2 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming domestic, agricultural, or livestock water-quality standards.

Overthrust Belt
The chemical composition of the Aspen confining unit in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as nine springs and one well. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS for springs issuing from the Aspen confining unit is shown on a trilinear diagram (**appendix F–5, diagram B**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram B**). TDS concentrations in the spring samples ranged from 107 to 228 mg/L, with a median of 195 mg/L. The TDS concentration in the well sample was 308 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Aspen confining unit in the OTB 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.

7.3.13 Sage Junction Formation

Present in the Overthrust Belt, the Upper Cretaceous Sage Junction Formation (**pl. 4**) is more than 3,000-ft thick and consists primarily of gray and tan siltstone, sandstone, and quartzite with minor amounts of porcellanite, limestone, conglomerate, and some coal beds (Rubey, 1973a, b; Lines and Glass, 1975, Sheet 1; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The formation is a lateral western stratigraphic equivalent to part of the Aspen Shale. The uppermost several hundred feet of the Sage Junction Formation may be equivalent in age to the lower part of the Upper Cretaceous Frontier Formation (Rubey, 1973b). The Sage Junction Formation is at least 3,375-ft thick above and to the west of the Absaroka thrust fault (**pl. 1**) and in the northwestern part of the Kemmerer area in the Bear River Basin south of the Snake/Salt River Basin (M'Gonigle and Dover, 1992). West and above the Absaroka thrust fault, the Upper Cretaceous lower member of the Evanston Formation unconformably overlies the Sage Junction Formation (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Changes in stratigraphic nomenclature between the western and eastern Cretaceous lithostratigraphic units occur at the Absaroka thrust fault in the Wyoming Overthrust Belt (Rubey, 1973b). Lithostratigraphic units located above and to the west of the Absaroka thrust, including the hanging wall of the fault, are the western units (Smiths, Thomas Fork, Cokeville, Quealy, and Sage Junction Formations), whereas those located below and to the east of the Absaroka thrust, including the footwall of the fault, are the eastern units (Bear River Formation and Aspen Shale) (**pl. 1; pl. 4**). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.14 Wayan Formation

The Upper and Lower Cretaceous Wayan Formation (**pl. 4**) consists of variegated mudstone, siltstone, and sandstone with minor porcellanite, bentonite, and coal (Oriel and Platt, 1980) (**pl. 4**). The formation is about 3,937-ft thick (Oriel and Platt, 1980). One spring discharge (10 gal/min) was inventoried for the formation as part of this study (**pl. 3**). No data were located describing the chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.15 Quealy Formation

The Upper Cretaceous Quealy Formation (**pl. 4**) consists of red and variegated pastel-tinted mudstone and minor interbedded pink, gray, and tan sandstone (Rubey, 1973b; Lines and Glass, 1975). The Quealy Formation thins eastward from about 1,100 ft in Idaho to about 500 ft in Wyoming (Oriel and Platt, 1980; Rubey and others, 1980). The Quealy Formation is the western stratigraphic equivalent of the middle to lower part of the Aspen Shale (Rubey, 1973b) (**plate 4**). No data were located describing the physical and chemical characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.16 Cokeville Formation

The Lower Cretaceous Cokeville Formation (**pl. 4**) consists of gray to tan fossiliferous sandstone, sandy siltstone, and light to dark gray claystone/mudstone with minor fossiliferous tan limestone; light gray, tan, and pink porcellanite; bentonite; and a few coal beds (Rubey, 1973b; Lines and Glass 1975; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The coal beds are located in the upper part of the Cokeville Formation (Rubey, 1973b). The Cokeville Formation thickens southeastward from about 850 ft in Idaho to about 3,000 ft in Wyoming (Oriel and Platt, 1980; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The upper part of the Cokeville Formation is the western stratigraphic equivalent of the lower part of the Aspen Shale, and the lower part of the formation is the western stratigraphic equivalent to the upper Bear River Formation (Rubey, 1973b) (**pl. 4**). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.17 Muddy Sandstone aquifer

The Muddy Sandstone aquifer is composed of the Lower Cretaceous Muddy Sandstone (**pls. 5** and **6**). The Muddy Sandstone consists of a 20- to 100-ft-thick rusty-brown to gray sandstone interbedded with black and gray siltstone and shale (Love, 1974a, 1975b, 2001c; Love and others, 1992; Love and Love, 2000). The formation is sometimes identified as a member of the underlying Thermopolis Shale (Love and others, 1992). The Muddy Sandstone aquifer is a major oil and gas reservoir in much of Wyoming. Because the lithostratigraphic unit is composed primarily of sandstone, the Muddy Sandstone was classified as an aquifer by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein), and throughout the State in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Muddy Sandstone are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as an aquifer was retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). In the subsurface, the Muddy Sandstone aquifer is confined from above by the Mowry confining unit and from below by the Thermopolis confining unit (**pls. 5** and **6**). No data were located describing the physical and chemical hydrogeologic characteristics of the hydrogeologic lithostratigraphic unit in the Snake/Salt River Basin.

7.3.18 Thermopolis confining unit

The Thermopolis confining unit is composed of the Lower Cretaceous Thermopolis Shale (**pls. 5** and **6**). The Thermopolis Shale primarily consists of black, flaky, soft shale (Love and others,

1992). The Thermopolis Shale is the northern and eastern stratigraphic equivalent to the Bear River Formation. Thickness of the Thermopolis Shale in the Gros Ventre Range ranges from 100 to 200 ft (Love and others, 1992; Love and Love, 2000; Love, 2001c, 2003c). Thickness of the Thermopolis Shale in the Overthrust Belt east of the Hoback fault ranges from 100 to 200 ft (Love and Love, 2000). North of Jackson Lake in the northern Teton Range, the Thermopolis Shale is only about 55-ft thick (Love and others, 1992). In the subsurface, the Thermopolis confining unit is overlain by the the Muddy Sandstone aquifer and underlain by the Cloverly aquifer (**pls. 5** and **6**).

Because the lithostratigraphic unit is composed primarily of shale, the Thermopolis Shale was classified as a confining unit by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein), and throughout the State in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Thermopolis Shale are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as a confining unit was retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Despite being classified as a confining unit, the Thermopolis confining unit likely can yield water locally in areas where discontinuous sandstone beds or zones with fractures (secondary permeability) are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Cox, 1976, Sheet 1). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.19 Bear River aquifer

The physical and chemical characteristics of the Bear River aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Lower Cretaceous Bear River Formation (**pl. 4**) consists of fissile black shale interbedded with brown fine-grained sandstone, and minor interbedded fossiliferous limestone and bentonite. Maximum thickness of the Bear River Formation in the Overthrust Belt ranges from less than 100 to about 1,800 ft (Jobin, 1965, 1972; Albee, 1968, 1973; Schroeder, 1973, 1974, 1976, 1979, 1981, 1987; Oriel and Platt, 1980; Schroeder and others, 1981; Oriel and Moore, 1985; Lageson, 1986; Love and others, 1992; Love, 2003c). Maximum thickness of the Bear River Formation in the Teton Range is about 1,000 ft (Oriel and Moore, 1985).

Previous investigators have classified the Bear River Formation as an aquifer, and that definition is retained herein (**pl. 4**). Berry (1955) identified the Bear River Formation as a potential aquifer in the Cokeville area in the Bear River Basin within the Overthrust Belt immediately south of the Snake/Salt River Basin. Robinove and Berry (1963, Plate 1) speculated that the Bear River Formation in the Bear River valley in the Overthrust Belt south of the Snake/Salt River Basin "possibly may yield small amounts of water." Lines and Glass (1975, Sheet 1) noted that "small quantities" of water were available from the discontinuous sandstone beds in the formation. In the Overthrust Belt, the Bear River Formation was identified as either "discontinuous aquifers with local confining beds" or a "minor aquifer" by Ahern and others (1981, Figure II-7, and Table IV-1) (**pl. 4**). Interbedded discontinuous sandstone beds compose the aquifer (Ahern and others, 1981; Lines and Glass, 1975, Sheet 1). In the Wyoming Water Framework Plan, the Bear River Formation was classified as a marginal aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**). Lines and Glass (1975, Sheets 1, 2) noted that some wells completed in the Bear River aquifer along the Snake River were abandoned because of hydrogen sulfide gas. Hydrogeologic data describing the Bear River aquifer in the Snake/Salt River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Bear River aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Bear 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–5**).

Overthrust Belt

The chemical composition of aquifers in the Bear River aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as four springs and eight wells. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS for springs issuing from and wells completed in the Bear River aquifer is shown on two trilinear diagrams (**appendix F–5, diagrams C** and **D**). TDS concentrations indicated that waters from all four springs and six of eight wells were fresh (TDS concentrations less than or equal to 999 mg/L), and waters from two of eight wells were slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L) (**appendix E–5; appendix F–5, diagrams C** and **D**). The TDS concentrations for the springs ranged from 226 to 264 mg/L, with a median of 248 mg/L. The TDS concentrations for the wells ranged from 197 to 1,120 mg/L, with a median of 504 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from the Bear River aquifer in the OTB 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.

Concentrations of some properties and constituents in water from wells completed in the Bear River aquifer in the OTB 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 and two constituents exceeded USEPA aesthetic standards for domestic use: TDS (4 of 8 samples exceeded the SMCL of 500 mg/L), pH (1 of 8 samples exceeded the upper SMCL limit of 8.5), chloride (1 of 8 samples exceeded the SMCL of 250 mg/L), and fluoride (1 of 7 samples exceeded the SMCL of 2 mg/L).

Concentrations of some characteristics and constituents in water from wells completed in the Bear River aquifer exceeded State of Wyoming standards for agricultural and livestock use in the OTB. One characteristic and two constituents in the wells approached or exceeded applicable State of Wyoming standards for agricultural-use standards: chloride (2 of 8 samples exceeded WDEQ Class II standard of 100 mg/L), SAR (1 of 8 samples exceeded the WDEQ Class II standard of 8), and sulfate (1 of 8 samples exceeded the WDEQ Class II standard of 200 mg/L). The value of one characteristic (pH) exceeded the livestock-use standard (1 of 8 samples exceeded upper WDEQ Class III standard of 8.5).

7.3.20 Thomas Fork aquifer

The Thomas Fork aquifer is composed of saturated and permeable parts of the Lower Cretaceous Thomas Fork Formation (**pl. 4**). The Thomas Fork Formation consists of variegated, banded, red, purple, brown, and green mudstone and minor interbedded gray to tan sandstone (Rubey, 1973b; Lines and Glass 1975; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). In part, the sandstone is conglomeratic with sediments (pebbles and cobbles) as large as 4 inches in diameter, and the mudstone contains gray to brown limestone nodules as large as several inches in diameter (Rubey, 1973b). The formation is about 2,000-ft thick in the southwestern part of Star Valley (Rubey, 1973b; Oriel and Platt, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The formation merges to the south with and is lithologically indistinguishable from the upper part

of the Early Cretaceous-age Kelvin Formation in northeastern Utah (Dover and M'Gonigle, 1993).

No data were located describing the physical and chemical characteristics of the Thomas Fork Formation in the Snake/Salt River Basin, but considerable insight into the hydrogeologic properties of the unit is provided by investigations in the Bear River Basin immediately to the south. Most information about the physical and chemical characteristics of the Thomas Fork aquifer was obtained through installation and subsequent testing of three wells completed in the aquifer to replace three springs as the water supply for the town of Cokeville in the Bear River Basin south of the Snake/Salt River Basin (Forsgren Associates, 1993b,c; TriHydro Corporation, 1993b, 2002, 2003). The Thomas Fork Formation is tentatively classified as an aquifer herein in the Snake/Salt River Basin based on these investigations. In fact, previous descriptions of the hydrogeologic characteristics of the Thomas Fork Formation were very limited. Lines and Glass (1975, Sheet 1) speculated that sandstone beds in the Thomas Fork Formation in the Overthrust Belt might yield "small quantities" of water to wells.

TriHydro Corporation (2002, p. 3-7) reported that sandstone beds composing the Thomas Fork aquifer in the Cokeville area typically were well cemented with calcite cement, and typically have poor intergranular porosity in "an unweathered and unfractured condition." Porosity and permeability were attributed to fractures in the sandstone beds composing the aquifer. Based on interpretation of aquifer tests conducted on the production wells, the investigators concluded that the Thomas Fork aquifer was a semiconfined, fracture-flow aquifer with primarily conduit flow. The investigators (TriHydro Corporation, 2002, p. 3-10) also conceptually described potential sources of recharge to the aquifer in the area. Potential sources of recharge identified were (1) streamflow losses and direct infiltration of precipitation and seepage to overlying lithostratigraphic units and subsequent movement of water in these units downward into the underlying Thomas Fork aquifer; and (2) direct infiltration of precipitation (rain and snow) on Thomas Fork aquifer outcrop areas.

7.3.21 Smiths Formation

The Lower Cretaceous Smiths Formation (**pl. 4**) consists of ferruginous black shale and interbedded tan, quartz-rich, very fine-grained sandstone. The black shale and tan sandstone are interbedded throughout the formation, but the upper unnamed member primarily is tan sandstone, and the lower unnamed member primarily is black shale (Rubey, 1973b; Rubey and others, 1980). The Smiths Formation thickens eastward from about 300 ft in Idaho to about 850 ft in Wyoming (Oriel and Platt, 1980; Rubey and others, 1980). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.22 Kootenai Formation

The Lower Cretaceous Kootenai Formation (**pl. 6**) consists of rusty thin-bedded sandstone, and grayish-red, soft claystone, white limestone, and chert-pebble conglomerate (Love and Christiansen, 1985, Sheet 2). Cox (1976, Sheet 1) speculated that sandstone in the Kootenai Formation probably would not yield more than a few gallons per minute per well. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.23 Cloverly aquifer

The Cloverly aquifer consists of saturated and permeable parts of the Lower Cretaceous Cloverly Formation in the Snake/Salt River Basin (**pls. 5** and **6**). The formation consists of two units in the Snake/Salt River Basin (Love and others, 1992). The upper unit is a 100- to 200-ft thick, olive-green, gray, and buff thin-bedded sandstone that commonly weathers to a rusty color and is informally known as the "rusty beds member." The lower unit is a 290- to 545-ft thick, variegated red, gray, lilac colored, and pink bentonitic claystone that commonly weathers to a "puffy surface;" thin beds of hard nodular dense cream-colored limestone also are present.

The Cloverly Formation is classified as an aquifer by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), and southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Cloverly Formation was a fair to poor aquifer (**pls. 5** and **6**). The Cloverly Formation is classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of sandstones in the Cloverly Formation likely are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as an aquifer was tentatively retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Cox (1976) noted that sandstone in the unit probably would not yield more than a few gallons per minute per well. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.3.24 Gannett aquifer and confining unit

The physical and chemical characteristics of the Gannett aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Gannett aquifer and confining unit is composed of the Lower Cretaceous Gannett Group (**pl. 4**). The Gannett Group consists of red sandy mudstone, sandstone, and chert-pebble conglomerate. Some thin limestone and dark gray shale are present in the upper part of the unit, and the lower part is more conglomeratic. Reported thicknesses vary. Thickness of the Gannett Group decreases from about 2,953 ft in Idaho to about 787 ft in Wyoming (Oriel and Platt, 1980).

In some areas, the Gannett Group is mapped as separate formations or groups of formations. The Gannett Group was described in detail by Eyer (1969) and Furer (1967, 1970). The Gannett Group is composed of five formations (in descending order from top to bottom): Smoot Formation, Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate.

The Smoot Formation of the Gannett Group was described as the unnamed upper redbed member until named by Eyer (1969). The Smoot Formation is composed of interbedded red mudstone and siltstone (Oriel and Platt, 1980). The Smoot Formation is absent in some local areas and is about 200-ft thick when combined with the underlying Draney Limestone (Oriel and Platt, 1980).

The Draney Limestone of the Gannett Group consists of dark to medium gray limestone, weathering light gray, very fine-crystalline to aphanitic limestone interbedded with dark gray calcareous shale and siltstone (Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980). The unit is about 200-ft thick when combined with the overlying Smoot Formation.

The Bechler Conglomerate of the Gannett Group is composed of red, red-gray, purple, and purple-gray, calcareous mudstone and siltstone, which becomes increasingly sandstone and chert-pebble conglomerate towards the west (Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980). A few thin limestone interbeds occur locally. The formation is about 1,300-ft thick.

The Peterson Limestone of the Gannett Group consists of light to medium gray and pastel-colored, weathering very light gray, very fine-crystalline limestone and pastel-colored calcareous mudstone (Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980). The unit is about 230-ft thick.

The basal Ephraim Conglomerate of the Gannett Group is composed of brick-red, red, orange-red, and maroon mudstone and siltstone; light gray, red, tan, and brown, crossbedded, coarse-grained calcareous to quartzitic sandstone; and red to brown, chert-pebble conglomerate. Thickness of

the Ephraim Conglomerate decreases eastward from about 3,300 ft in Idaho to about 490 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980; M'Gonigle and Dover, 1992).

Permeability in the Gannett Group likely is small on a regional scale, and thus, in most areas the unit is capable of yielding only small quantities of water locally. However, more permeable water-bearing parts of the Gannett Group capable of yielding larger quantities of water are present in the conglomeratic formations (Bechler and Ephraim Conglomerates) and in areas where fractures and solution openings (secondary permeability) are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern and others, 1981, Table IV-1). In addition, sandstone beds in the lower part of the Gannett Group also may be permeable and water-bearing (Ahern and others, 1981, Table IV-1). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Smoot Formation and Ephraim Conglomerate might be poor to fair aquifers; the Draney Limestone might be a poor aquifer (?); the Bechler Conglomerate might be a poor aquifer; and the Peterson Limestone might be a fair to poor aquifer (?) in the Snake/Salt River Basin (**pl. 4**). Ahern and others (1981, Figure II-7) classified the Gannett Group as a series of "discontinuous aquifers with local confining units" in the Overthrust Belt and the adjacent Green River Basin (**pl. 4**). Glover (1990) considered the Ephraim Conglomerate of the Gannett Group (identified as a conglomerate near the base of the Gannett Group) to be a minor aquifer in the Evanston area in the Bear River valley in the Overthrust Belt to the south of the Snake/Salt River Basin. He also noted that aquifers in the Gannett Group were hydraulically isolated from the overlying Evanston aquifer (Hams Fork Conglomerate Member of the Evanston Formation), Wasatch aquifer, and Bear River alluvial aquifer. TriHydro Corporation (1993b, p. II-3) reported that the Ephraim Conglomerate produced about 10 gal/min during drilling of a test boring at the Spring Creek anticline near Cokeville in the Bear River Basin to the south of the Snake/Salt River Basin. In the Wyoming Water Framework Plan, the Gannett Group was classified as a marginal aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**).

Because the unit has low overall permeability, but has distinct zones and formations of higher permeability with potential to yield water to wells, the Gannett Group was classified as both an aquifer and confining unit herein (**pl. 4**). Few hydrogeologic data describing the Gannett aquifer and confining unit in the Snake/Salt River Basin are available, but spring-discharge and well-yield measurements inventoried as part of this study are shown on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Gannett aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Gannett 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–5**).

Overthrust Belt

The chemical composition of groundwater in the Gannett aquifer and confining unit in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from three springs and one well. Individual constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS for springs issuing from the Gannett aquifer and confining unit is shown on a trilinear diagram (**appendix F–5, diagram E**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram E**). The TDS concentrations for the springs ranged from 141 to 228 mg/L, with a median of 208 mg/L. The TDS concentration for the well was 318 mg/L.

On the basis of the characteristics and constituents analyzed for, the quality of water from springs issuing from the Gannett aquifer and confining

unit in the OTB 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.

On the basis of the characteristics and constituents analyzed for, the quality of water in the one well sample completed in the Gannett aquifer and confining unit in the OTB was suitable for most uses. One characteristic (pH) had a value outside the range for USEPA aesthetic standards for domestic use and WDEQ livestock-use standards (above upper SMCL and WDEQ Class III limit of 8.5). No characteristics or constituents had concentrations that exceeded State of Wyoming agricultural standards.

7.3.25 Morrison confining unit

The Upper Jurassic Morrison Formation comprises the Morrison confining unit in the Snake/Salt River Basin (**pls. 5** and **6**). The Morrison Formation consists of buff and gray sandstone interbedded with red, green, and gray siltstone and claystone (Love and others, 1992). Thickness of the formation ranges from 185 to 250 ft (Love and others, 1992).

The Morrison Formation is classified as a confining unit, an aquifer, or both, by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), and southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Morrison Formation was probably a poor aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The Morrison Formation is classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Morrison Formation generally are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as a confining unit was tentatively retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Cox (1976, Sheet 1) noted that the unit probably would not yield more than a few gallons per minute per well in northwestern Wyoming. No data were located in the Snake/Salt River Basin describing the physical and chemical characteristics of the hydrogeologic unit.

7.3.26 Ellis Group

In the Yellowstone Volcanic Area in the Snake/Salt River Basin, the Middle Jurassic Ellis Group is composed of three different formations—the Swift, Rierdon, and Sawtooth Formations (Love and Christiansen, 1985, Sheet 2) (**pl. 1**; **pl. 6**). The Swift Formation consists of calcareous, glauconitic sandstone and sandy limestone. The Rierdon Formation consists of mudstone, siltstone, shale, and basal limestone. The Sawtooth Formation consists of redbeds and limestone. No data were located describing the physical and chemical characteristics of the Ellis Group in the Snake/Salt River Basin.

7.3.27 Sundance aquifer

The Middle and Upper Jurassic Sundance Formation comprises the Sundance aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The formation consists of two lithologic units in the Snake/Salt River Basin. The upper unit consists of glauconitic gray, buff, and green very calcareous sandstone with a few thin shale beds and very fossiliferous limestone beds (Love and others, 1992). Thickness of the upper unit ranges from 75 to 140 ft. The lower unit consists of gray calcareous plastic to splintery shale, clayey limestone, hard oolitic limestone, and one or more zones of red, soft, plastic shale (Love and others, 1992). The lower unit is marine in origin and is highly fossiliferous. Thickness of the lower unit ranges from 400 to 550 ft.

Cox (1976, Sheet 1) speculated that the unit may yield a few gallons per minute per well from sandstone and from fractures and solution channels in limestone. No data were located in the Snake/Salt River Basin describing the physical and chemical characteristics of the hydrogeologic unit.

7.3.28 Stump Formation

The physical and chemical characteristics of the Stump Formation in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Upper to Middle Jurassic Stump Formation (**pl. 4**) consists of interbedded light to dark green, green-gray, glauconitic, fine-grained sandstone, siltstone, and limestone (Lines and Glass, 1975; Oriel and Platt, 1980; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). Pipiringos and Imlay (1979) divided the Stump Formation into two members—the Upper Jurassic Redwater Member and the Middle Jurassic Curtis Member (individual members not shown on Plate 4). The Stump Formation ranges in thickness from 92 ft to at least 400 ft in the Overthrust Belt area, and thins irregularly to the north and east from the thickest section in southeastern Idaho (Pipiringos and Imlay, 1979; Oriel and Platt, 1980; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The upper member of the Stump Formation is similar to the silty to sandy facies of the Redwater Member of the Sundance Formation eastward in Wyoming, whereas the lower member is similar to the Curtis Formation in the San Rafael Swell area of central Utah (Pipiringos and Imlay, 1979).

The Redwater Member of the Stump Formation consists of two lithologic units (Pipiringos and Imlay, 1979). The upper lithologic unit is composed of gray, green-gray, nearly white, glauconitic, thin- to thick-bedded, crossbedded sandstone with minor interbeds of sandy siltstone, clayey siltstone, and oolitic, sandy limestone, which locally contains chert pebbles, belemnite fossils, and ammonite fossils. The lower lithologic unit is composed of yellow-gray to brown, glauconitic siltstone and claystone, which is locally sandy and contains belemnite fossils.

The Curtis Member of the Stump Formation consists of two lithologic units (Pipiringos and Imlay, 1979). The upper lithologic unit is composed of green-gray to olive-green, soft, flaky to fissile claystone with minor thin interbeds of sandstone and oolitic, fossiliferous limestone. The lower lithologic unit is composed of green-gray to brown-gray, glauconitic, thin- to thick-bedded, ripple-marked, crossbedded, fine- to very fine-grained sandstone (some silty and medium-grained sandstone).

Little information is available describing the hydrogeologic characteristics of the Stump Formation. Robinove and Berry (1963, Plate 1) speculated that the Stump Formation was likely to yield small quantities of groundwater to wells in the Bear River valley in the Overthrust Belt south of the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Stump Formation was a fair to poor (?) aquifer in the Snake/Salt River Basin (**pl. 4**). Lines and Glass (1975, Sheet 1) noted that rocks in the Stump Formation in the Overthrust Belt were relatively impermeable and in most areas were probably capable of yielding only small quantities of water. Ahern and others (1981, Figure II-7, Table IV-1) classified the Stump Formation as a confining unit [aquitard] or poor aquifer (**pl. 4**). Few hydrogeologic data are available describing the Stump Formation, but well-yield and spring-discharge measurements inventoried for the lithostratigraphic unit in the Snake/Salt River Basin are summarized in **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Stump Formation in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Stump Formation 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–3** and **E–5**).

Jackson Hole

The chemical composition of the Stump Formation in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental

water sample from one spring. Individual constituents are listed in **appendix E–3**. The TDS concentration (245 mg/L) indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Stump Formation in JH 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.

Overthrust Belt
The chemical composition of groundwater in the Stump Formation in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–5**. The TDS concentration (241 mg/L) indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Stump Formation in the OTB 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.

7.3.29 Preuss Sandstone or Redbeds

The Middle Jurassic Preuss Sandstone or Redbeds (**plate 4**) consists of interbedded purple, maroon, dull red, purple-gray, and red-gray, siltstone, sandy siltstone, silty claystone, and claystone with minor interbedded halite (rock salt), alum, and gypsum locally present in irregular zones (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey and others, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). Beds of red, gray, and tan, fine-grained, thin-bedded and regular-bedded sandstone also are present. Formation thickness decreases eastward from about 1,640 ft in Idaho to 360 ft in Wyoming (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey and others, 1980). The Preuss Sandstone or Redbeds are overlain by the Stump Formation and underlain by the Twin Creek Limestone (**pl. 4**).

Little information is available describing the hydrogeologic characteristics of the Preuss Sandstone or Redbeds. Robinove and Berry (1963, Plate 1) speculated that the Preuss Sandstone or Redbeds were likely to yield small quantities of groundwater to wells in the Bear River valley in the Overthrust Belt to the south of the Snake/Salt River Basin,. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Preuss Sandstone or Redbeds likely were a poor aquifer (?) in the Snake/Salt River Basin (**pl. 4**). Lines and Glass (1975, Sheet 1) noted that rocks in the Preuss Sandstone or Redbeds were relatively impermeable and in most areas were probably capable of yielding only small quantities of water. Ahern and others (1981, Figure II-7, Table IV-1) classified the formation as a confining unit [aquitard] or poor aquifer (**pl. 4**). No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

In outcrop and shallow groundwater areas, bedded halite (rock salt) in the lower part of the formation has been removed by dissolution (Imlay, 1952). In areas where evaporite beds have been removed by dissolution, breccia zones and collapse structures may have formed and consequently, may have increased permeability.

7.3.30 Twin Creek aquifer

The physical and chemical characteristics of the Twin Creek aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Twin Creek aquifer is composed of the Middle Jurassic Twin Creek Limestone (**pl. 4**). The Twin Creek Limestone consists of green-gray argillaceous (shaly) limestone and calcareous siltstone. Thickness of the formation decreases eastward from about 3,300 ft in Idaho to about 440 ft in Wyoming (Imlay, 1967; Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980;

M'Gonigle and Dover, 1992). The formation is as much as 2,900-ft thick above and to the west of the Absaroka thrust fault (WSGS Plate 1?). Thickness of the Twin Creek Limestone below and to the east of the Absaroka thrust fault in the Kemmerer area in the Bear River Basin south of the Snake/Salt River Basin ranges from 800 to 1,000 ft (M'Gonigle and Dover, 1992). The Twin Creek Limestone was deposited in a Jurassic seaway marine environment, as reflected by the presence of pelecypod fossils such as *Gryphaea* (Imlay, 1967). Imlay (1967) defined and described seven members of the Twin Creek Formation in the Overthrust Belt of Wyoming-Idaho-Utah. These members are, from youngest (top) to oldest (bottom): Giraffe Creek Member, Leeds Creek Member, Watton Canyon Member, Boundary Ridge Member, Rich Member, Sliderock Member, and Gypsum Spring Member (individual members not shown on Plate 4).

The Giraffe Creek Member of the Twin Creek Limestone consists of yellow-gray, green-gray, and pink-gray, silty to sandy, ripple-marked, thin-bedded limestone and sandstone with minor thick interbeds of oolitic sandy limestone. Sand and glauconite content increases to the west, and the Giraffe Creek Member of the Twin Creek Limestone grades upward into red, soft siltstone at the base of the Preuss Sandstone or Redbeds. Thickness decreases eastward and northward from 295 to 25 ft (Imlay, 1967).

The Leeds Creek Member of the Twin Creek Limestone consists of light gray, dense, shaly, soft limestone, which weathers into slender splinters, and minor interbeds of oolitic silty or sandy, ripple-marked limestone. Clay content increases to the northeast in Idaho and Wyoming and to the south in Utah. The Leeds Creek Member is the least resistant member of the Twin Creek Limestone and commonly forms valleys in outcrop areas. The Leeds Creek Member of the Twin Creek Limestone grades upward into the harder, silty to sandy, basal limestone of the overlying Giraffe Creek Member. Thickness decreases eastward from about 1,600 to 260 ft (Imlay, 1967).

The Watton Canyon Member of the Twin Creek Limestone consists of gray, compact, dense, brittle, medium- to thin-bedded limestone, which forms prominent cliffs and ridges. The basal unit of the Watton Canyon Member generally is massive and oolitic, and some oolitic limestone interbeds occur throughout the unit. The upper part of the Watton Canyon Member grades upward into the shaly, soft basal limestone of the overlying Leeds Creek Member and contains pelecypod fossils. Thickness of the Watton Canyon Member decreases eastward from about 400 to 60 ft (Imlay, 1967).

The Boundary Ridge Member of the Twin Creek Limestone consists of red, green, and yellow, soft siltstone with interbedded silty to sandy or oolitic limestone. The Boundary Ridge Member grades eastward into red, gypsiferous, soft siltstone and claystone, and grades westward into cliff-forming, oolitic to dense limestone with minor interbedded red siltstone. The Boundary Ridge Member is overlain by the cliff-forming, basal limestone of the Watton Canyon Member. Thickness decreases eastward from about 285 to 30 ft (Imlay, 1967).

The Rich Member of the Twin Creek Limestone consists of gray, shaly limestone that is very soft at the base; clay content increases to the north, and the upper part grades into the basal hard sandy limestone or red, soft siltstone of the Boundary Ridge Member of the Twin Creek Limestone. Pelecypod and cephalopod fossils are present. Thickness of the Rich Member decreases eastward from 500 to 40 ft (Imlay, 1967).

The Sliderock Member of the Twin Creek Limestone consists of gray-black, medium- to thin-bedded limestone with oolitic basal beds, and commonly forms a low ridge between adjacent members. Pelecypod and cephalopod fossils are present. Thickness of the Sliderock Member decreases eastward from 285 to 20 ft (Imlay, 1967).

The Gypsum Spring Member of the Twin Creek Limestone consists of red to yellow, soft siltstone and claystone, interbedded with brecciated, vuggy, or chert-bearing limestone. In Wyoming, a basal unit of brecciated limestone is present and grades eastward into thick, massive gypsum deposits.

The chert-bearing limestone thickens westward from a few feet thick in Wyoming to a thick, cliff-forming unit in Idaho. Locally, the top bed of the Gypsum Spring Member is a green tuff. Thickness of the Gypsum Spring Member decreases eastward from 400 to 12 ft (Imlay, 1967). In some areas of Wyoming, including parts of the Snake/Salt River Basin, the Gypsum Spring Member of the Twin Creek Limestone has been elevated to formation rank and is referred to as the Gypsum Spring Formation (Love and others, 1993).

The Twin Creek Limestone is classified as an aquifer or potential aquifer by previous investigators and that classification is retained herein (**pl. 4**). Robinove and Berry (1963, Plate 1) speculated that the Twin Creek Limestone was likely to yield small quantities of groundwater to wells in the Bear River valley in the Overthrust Belt to the south of the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Twin Creek Limestone was a poor aquifer (?) in the Snake/Salt River Basin (**pl. 4**). Lines and Glass (1975, Sheet 1) noted that permeability in the upper part of the Twin Creek Limestone likely was low compared to the lower part and thus, the formation likely would yield small quantities of water to wells completed in the upper part of the unit. The investigators noted that limestone in the lower part of the Twin Creek Limestone is brecciated and honeycombed; thus, wells completed in the lower part of the formation were more likely to yield moderate quantities of water (Lines and Glass, 1975, Sheet 1). In the Wyoming Water Framework Plan, the Twin Creek Limestone was classified as a minor aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**). Hydrogeologic data describing the Twin Creek aquifer, including spring-discharge measurements and other hydraulic properties, are summarized on **pl. 3**.

The Twin Creek aquifer likely is in hydraulic connection with the underlying Nugget aquifer (Lines and Glass, 1975, Sheet 1; Ahern and others, 1981). In fact, Lines and Glass (1975, Sheet 1) noted that few springs issue from the lower part of the Twin Creek Limestone, possibly because the overlying unit may be in hydraulic connection with, and "drain into" the underlying Nugget aquifer. Clarey (2011) speculated that groundwater from the Gypsum Spring Member in areas where gypsum deposits are present may have the potential for calcium-sulfate-type waters and large TDS concentrations.

Chemical characteristics

The chemical characteristics of groundwater from the Twin Creek aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Twin Creek 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–2, E–5,** and **E–6**).

Northern Ranges

The chemical composition of the Twin Creek aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–2**. The TDS concentration (256 mg/L) indicated that the water was fresh (concentration less than or equal to 999 mg/L) (**appendix E–2**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Twin Creek aquifer in the NR 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.

Overthrust Belt

The chemical composition of groundwater in the Twin Creek aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 springs. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS concentrations for springs issuing from the Twin Creek aquifer is shown on a trilinear diagram (**appendix F–5, diagram F**). TDS concentrations

indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram F**). The TDS concentrations for the springs ranged from 133 to 326 mg/L, with a median of 219 mg/L. On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Twin Creek aquifer in the OTB 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.

Star Valley

The chemical composition of the Twin Creek aquifer in the Star Valley (SV) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–6**. The TDS concentration (614 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–6**).

Concentrations of some properties and constituents in water from a spring issuing from the Twin Creek aquifer in the SV 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 USEPA aesthetic standards for domestic use: TDS (exceeded SMCL limit of 500 mg/L) and sulfate (exceeded SMCL of 250 mg/L). One constituent in the spring approached or exceeded applicable State of Wyoming standards for agricultural-use standards: sulfate (exceeded WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.3.31 Gypsum Spring confining unit

The physical and chemical characteristics of the Gypsum Spring confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Gypsum Spring confining unit is composed of the Middle Jurassic Gypsum Spring Formation (**pls. 5** and **6**). The Gypsum Spring Formation consists of dark-red soft shale, underlain by and interbedded with slabby gray dolomite and white gypsum. In most outcrop areas, gypsum in the formation has been leached, leaving lithified carbonate breccia that forms rounded cliffs (Love and others, 1992). Thickness of the formation ranges from 50 to 150 ft, depending on amount of leaching of gypsum (Love and others, 1992).

The Gypsum Spring Formation is classified as a confining unit, aquifer, or both by previous investigators in the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), and southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Gypsum Spring Formation was a poor aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). The Gypsum Spring Formation was classified as a marginal aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because of lithologic characteristics of the Gypsum Spring Formation in the study area (described above), the lithostratigraphic unit was tentatively classified as a confining unit in the Snake/Salt River Basin (**pls. 5** and **6**). One spring discharge was inventoried as part of this study for the Gypsum Spring confining unit in the Snake/Salt River Basin (**pl. 3**).

Chemical characteristics

The chemical characteristics of groundwater from the Gypsum Spring confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Gypsum Spring 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–2**).

Northern Ranges
The chemical composition of the Gypsum Spring confining unit in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–2**. The TDS concentration (2,190 mg/L) indicated that the water was slightly saline (TDS concentration ranging from1,000 to 2,999 mg/L) (**appendix E–2**).

Concentrations of some properties and constituents in water from the spring issuing from the Gypsum Spring confining unit in the NR 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 USEPA aesthetic standards for domestic use and State of Wyoming standards for agricultural use: TDS (exceeded SMCL limit of 500 mg/L and WDEQ Class II standard of 2,000 mg/L) and sulfate (exceeded SMCL of 250 mg/L and WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.3.32 Nugget aquifer

The physical and chemical characteristics of the Nugget aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Nugget aquifer is composed of the Triassic (?) to Jurassic (?) Nugget Sandstone (**pls. 4**, **5**, and **6**). The Nugget Sandstone consists of tan to pink, crossbedded, well-sorted, quartz-rich sandstone (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey and others, 1980; Love and others, 1992). The Nugget Sandstone has been interpreted as deposited as an eolian (wind-blown) sand dune sequence from a desert or a beach environment. Reported maximum thickness of the Nugget Sandstone in the Northern Ranges (Teton and Gros Ventre Ranges) ranges from about 100 to 400 ft (Pampeyan and others, 1967; Oriel and Moore, 1985; Love and others, 1992; Love, 2001a,b,c). Reported maximum thickness of the Nugget Sandstone in the Overthrust Belt ranges from about 250 to 984 ft (Jobin, 1965, 1972; Pampeyan and others, 1967; Schroeder, 1969, 1972, 1973, 1974, 1976, 1979, 1981; Albee, 1968, 1973; Albee and Cullins, 1975; Oriel and Platt, 1980; Schroeder and others, 1981; Love and others, 1992; Love, 2003c).

The Nugget Sandstone is classified as an aquifer by all investigators and that classification is retained herein (**pls. 4**, **5,** and **6**). Robinove and Berry (1963, Plate 1) speculated that the Nugget Sandstone was likely to yield small quantities of groundwater to wells in the Bear River valley in the Overthrust Belt to the south of the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Nugget aquifer was a fair to good aquifer in the Snake/Salt River Basin (**pls. 4**, **5,** and **6**). Lines and Glass (1975, Sheet 1) considered the Nugget Sandstone to be the "best aquifer" in their "hydrogeologic division 4" (identified as being composed of Jurassic- and Cretaceous-age sandstone and limestone and shown on **pls. 4** and **5**) in the Overthrust Belt. The investigators (Lines and Glass, 1975, Sheet 1) reported that the Nugget aquifer was capable of yielding moderate to large quantities of water where "outcrop or recharge areas are large, where bedding is continuous and not offset by faults, and in topographic lows where large thickness of sandstone is saturated." Furthermore, the investigators (Lines and Glass, 1975, Sheet 1) noted that few springs issue from the lower part of the Twin Creek Limestone, possibly because the overlying unit may be in hydraulic connection with, and "drain into" the underlying Nugget aquifer. Springs commonly issue from the Nugget aquifer in the Overthrust Belt (Lines and Glass, 1975, Sheet 1) (also see **pl. 3**). In the Wyoming Water Framework Plan, the Nugget Sandstone was classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Spring-discharge and well-yield measurements for the Nugget aquifer in the Snake/Salt River Basin inventoried as part of this study

are summarized in **plate 3**.

Ahern and others (1981, Figure II-7, and Table IV-1) classified the Nugget Sandstone as a major aquifer in the Overthrust Belt and the adjacent Green River Basin (**pls. 4** and **5**). The Nugget aquifer was considered to be part of an aquifer system, identified as the Nugget aquifer system, composed of the overlying Twin Creek Limestone and the underlying Ankareh Formation and Thaynes Limestone in the Overthrust Belt (**pl. 4**). The investigators noted that porosity and permeability in the Nugget aquifer were "good," especially in the crossbedded upper part. The investigators also speculated that smaller transmissivities for the Nugget aquifer in the adjacent Green River Basin may be attributable to increased lithostatic pressure (deeper burial) and decreased fracture occurrence.

Clarey (2011) noted that the upper part of the Nugget Sandstone in some areas of the Overthrust Belt has calcite (calcium carbonate) cement with slightly increased permeability, and that the lower part of the formation has siliceous (quartz) cement with decreased permeability. The investigator reported that this "dual cementation feature" of the Nugget Sandstone has been observed in an oilfield production well located to the northeast of Evanston in Uinta County, Wyoming.

Chemical characteristics

The chemical characteristics of groundwater from the Nugget aquifer in the Snake/Salt River Basin are described in this section of the report. 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 (**appendix E–5**).

Overthrust Belt
The chemical composition of groundwater in the Nugget aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 springs and 1 well. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS concentrations for springs issuing from the Nugget aquifer is shown on a trilinear diagram (**appendix F–5, diagram G**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram G**). The TDS concentrations in the spring samples ranged from 30.0 to 388 mg/L, with a median of 106 mg/L. The TDS concentration in the well sample was 269 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Nugget aquifer in the OTB 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.

7.3.33 Chugwater aquifer and confining unit

The physical and chemical characteristics of the Chugwater aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Chugwater aquifer and confining unit is composed of the Upper and Lower Triassic-age Chugwater Formation (**pls. 5** and **6**). The Chugwater Formation is composed of four members (Love and others, 1992) (individual members not shown on Plates 5 and 6). The uppermost unit, the Popo Agie Member, consists of ocher and purple claystone, red shale, lenticular purple limestone-pellet conglomerate, and red siltstone, ranging in thickness from 75 to 300 ft. The next lower unit, the Crow Mountain Sandstone Member, consists of red to salmon-pink soft porous sandstone containing large rounded quartz grains in a finer matrix, ranging in thickness from 50 to 100 ft. The next lower unit, the Alcova Limestone Member, consists of gray and purple thin-bedded hard limestone and dolomite with interbeds of white gypsum, ranging in thickness from 10 to 60 ft. The lowermost unit is the Red

Peak Member, which consists of red gypsiferous siltstone and very fine grained sandstone containing some red shale partings, ranging in thickness from 800 to 1,275 ft.

The Chugwater Formation is classified as a confining unit, an aquifer, or both, by previous investigators (**pls. 5** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Chugwater Formation was probably a fair to poor aquifer (?) in the Snake/Salt River Basin (**pls. 5** and **6**). In the eastern Gros Ventre Range, the Chugwater Formation was combined by Mills (1989) and Mills and Huntoon (1989) with the underlying Dinwoody and Phosphoria Formations into a single confining unit that overlies and confines the underlying Tensleep aquifer (**pl. 5**). In the adjacent Wind River and Bighorn Basins east of the Snake/Salt River Basin (Bartos and others, 2012, and references therein), and southeast in the Green River Basin (Bartos and Hallberg, 2010, and references therein), the Chugwater Formation was classified as both aquifer and confining unit (**pls. 5** and **6**). The Chugwater Formation is classified as either a marginal aquifer or major aquitard in the Wyoming Water Framework Plan, depending upon area of occurrence (WWC Engineering and others, 2007, Figure 4-9) (**pls. 5** and **6**). Because lithologic characteristics of the Chugwater Formation generally are similar in all Wyoming structural basins, classification of the lithostratigraphic unit as both an aquifer and confining unit was tentatively retained herein for the Snake/Salt River Basin (**pls. 5** and **6**). Cox (1976, Sheet 1) noted that the unit probably would not yield more than a few gallons per minute per well in northwestern Wyoming. Few hydrogeologic data are available describing the Chugwater aquifer and confining unit in the Snake/Salt River Basin, but two well-yield measurements were inventoried as part of this study and are presented on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Chugwater aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Chugwater 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–2**).

Northern Ranges

The chemical composition of the Chugwater aquifer and confining unit in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituents are listed in **appendix E–2**. The TDS concentrations (153 and 1,340 mg/L) indicated that the waters were fresh and slightly saline (TDS concentrations less than or equal to 999 mg/L, and TDS concentrations greater than or equal to 1,000 and less than or equal to 2,999 mg/L, respectively).

Concentrations of some properties and constituents in water from the Chugwater aquifer and confining unit in the NR approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: TDS (1 of 2 samples exceeded SMCL limit of 500 mg/L) and sulfate (1 of 2 samples exceeded SMCL of 250 mg/L). One constituent approached or exceeded applicable State of Wyoming standards for agricultural-use standards: sulfate (1 of 2 samples exceeded WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.3.34 Ankareh aquifer

The physical and chemical characteristics of the Ankareh aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Ankareh aquifer is composed of the Upper Triassic Ankareh Formation (**pl. 4**). The Ankareh

Formation consists of red and maroon shale and pale purple limestone with minor white to red, fine-grained, quartz-rich sandstone; thickness of the formation increases eastward from about 460 ft in Idaho to about 920 ft in Wyoming (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). In central Wyoming, the Ankareh Formation is the stratigraphic equivalent of the upper part of the Chugwater Group or Formation (including the Red Peak Member, Alcova Limestone Member, unnamed redbeds of interbedded siltstone and sandstone, and Popo Agie Member of the Chugwater Group or Formation) (Kummel, 1954). The sandstone may correlate westward to the Timothy Sandstone Member of the Thaynes Limestone, and the limestone may correlate westward to the Portneuf Limestone Member of the Thaynes Limestone (Kummel, 1954). Redbeds present below the thin limestone or sandstone in the Ankareh Formation may correlate westward to the Lanes Tongue of the Ankareh Formation (Kummel, 1954).
Previous investigators have defined the Ankareh Formation as an aquifer, and that definition is tentatively retained herein (**pl. 4**). Robinove and Berry (1963, Plate 1) speculated that the Ankareh Formation was likely to yield small quantities of groundwater to wells in the Bear River valley to the south of the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Ankareh Formation was probably a poor aquifer in the Snake/Salt River Basin (**pl. 4**). Lines and Glass (1975, Sheet 1) noted that rocks in the Ankareh Formation were relatively impermeable in most areas, but that the unit was probably capable of yielding small quantities of water locally. Ahern and others (1981, Figure II-7, and Table IV-1) defined the Ankareh Formation as a minor aquifer or minor regional aquifer (locally confining) in the Overthrust Belt (**pl. 4**). Spring-discharge measurements for the Ankareh aquifer in the Snake/Salt River Basin inventoried as part of this study are summarized in **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Ankareh aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Ankareh 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–2 and E–5**).

Northern Ranges
The chemical composition of the Ankareh aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–2**. The TDS concentration (256 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–2**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Ankareh aquifer in the NR 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.

Overthrust Belt
The chemical composition of groundwater in the Ankareh aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs. Individual constituents are listed in **appendix E–5**. The TDS concentrations (263 and 364 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Ankareh aquifer in the OTB 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.

7.3.35 Thaynes aquifer

The physical and chemical characteristics of the Thaynes aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Thaynes aquifer is composed of saturated and permeable parts of the Upper and Lower Triassic Thaynes Limestone (**pl. 4**). The Thaynes Limestone consists of gray limestone and brown-weathering, gray, calcareous siltstone with abundant dark gray shale and abundant limestone in the lower part of the formation (Lines and Glass, 1975; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). Thickness of the Thaynes Limestone in the Overthrust Belt ranges from about 250 to 1,640 ft (Jobin, 1965, 1972; Pampeyan and others, 1967; Albee, 1968, 1973; Schroeder, 1969, 1973, 1979, 1981, 1987; Albee and Cullins, 1975; Oriel and Platt, 1980; Schroeder and others, 1981; Oriel and Moore, 1985; Lageson, 1986; Love and others, 1992). Thickness of the Thaynes Limestone in the Teton Range ranges from about 110 to 1,640 ft (Pampeyan and others, 1967; Oriel and Moore, 1985).

Kummel (1954) defined several members of the Thaynes Limestone and the interfingering Ankareh Formation, which the investigator considered a member of the Thaynes Limestone (individual members not shown on Plate 4). The Timothy Sandstone Member is the uppermost member of the Thaynes Limestone and is missing at some locations. The Timothy Sandstone Member consists of red siltstone, shale, and sandstone at Hot Springs along Indian Creek in southeastern Idaho and rapidly thins eastward into Wyoming. In adjacent Idaho, the Timothy Sandstone Member was removed by Trimble (1982) as a member of the Thaynes Limestone and was elevated to formation rank because of its "nonmarine origin." The Portneuf Limestone Member of the Thaynes Limestone consists of olive-gray, massive limestone and olive-light tan calcareous siltstone. The Lanes Tongue of the Thaynes Limestone consists of red, interbedded shale and siltstone. The redbeds member is similar to the overlying Ankareh Formation. The upper calcareous siltstone member consists of light tan, thin- to massively-bedded, silty limestone and calcareous siltstone. The middle shale member of the Thaynes Limestone consists of black shale and shaly limestone with cephalopod, ammonite, and pelecypod fossils. The lower shale member of the Thaynes Limestone is composed of dark gray, silty limestone. The lower limestone member of Thaynes Limestone consists of gray-blue to gray (weathers gray), massive limestone with cephalopod fossils.

Previous investigators generally have defined the Thaynes Limestone as an aquifer and that definition is retained herein (**plate 4**). Robinove and Berry (1963, Plate 1) speculated that the Thaynes Limestone was likely to yield small quantities of groundwater to wells in the Bear River valley to the south of the Snake/Salt River Basin. Lines and Glass (1975, Sheet 1) considered the Thaynes Limestone to be the "best aquifer" in their "hydrogeologic division 3" (identified as being composed of Triassic and Permian siltstones and limestones and shown on **plate 4**) in the Overthrust Belt. Ahern and others (1981, Figure II-7, and Table IV-1) defined the Thaynes Limestone as a major aquifer or regional aquifer in the Overthrust Belt. In contrast to these previous investigators, the Wyoming Water Planning Program (1972, Table III-2) speculated that the Thaynes Limestone was a confining unit in the Snake/Salt River Basin (**pl. 4**). Limestone in the Thaynes aquifer likely yields moderate quantities of water to wells; yields are greatest in areas with bedding-plane partings and where secondary permeability in the form of fractures or solution openings, or both, has developed (Lines and Glass, 1975, Sheet 1; Ahern and others, 1981, Figure II-7, and Table IV-1). Spring-discharge measurements and other hydraulic properties for the Thaynes aquifer in the Snake/Salt River Basin inventoried as part of this study are summarized in **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Thaynes aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Thaynes 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–5**).

Overthrust Belt
The chemical composition of groundwater in the Thaynes aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as six springs. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major-ion composition in relation to TDS concentrations for the six springs is shown on a trilinear diagram (**appendix F–5, diagram H**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; Appendix F–5, diagram H**). The TDS concentrations for the springs ranged from 89.0 to 281 mg/L, with a median of 186 mg/L. On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Thaynes aquifer in the OTB 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.

7.3.36 Woodside confining unit

The physical and chemical characteristics of the Woodside confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Woodside confining unit is composed of the Lower Triassic Woodside Shale (**pl. 4**). The Woodside Shale consists of interbedded red siltstone and shale with minor sandstone and gray limestone interbeds; thickness increases eastward across the Overthrust Belt from about 390 ft in Idaho to about 650 ft in Wyoming (Kummel, 1954; Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). The Woodside Formation overlies the Dinwoody Formation and is overlain by the Thaynes Limestone in the Overthrust Belt in the Snake/Salt River Basin (**pl. 4**). The upper part of the Woodside Shale is stratigraphically equivalent to the Red Peak Member of the Chugwater Group or Formation (Kummel, 1954).

Little information is available describing the hydrogeologic characteristics of the Woodside Shale. Robinove and Berry (1963, Plate 1) speculated that the Woodside Shale was likely to yield small quantities of groundwater to wells in the Bear River valley to the south of the Snake/Salt River Basin. The Wyoming Water Planning Program (1972, Table III-2) speculated that the Woodside Shale was a poor aquifer in the Snake/Salt River Basin (**pl. 4**). Lines and Glass (1975, Sheet 1) noted that rocks in the Woodside Shale were relatively impermeable in the Overthrust Belt and in most areas were probably capable of yielding only small quantities of water. Ahern and others (1981, Figure II-7) classified the formation as an aquitard (confining unit and that definition is tentatively retained herein (**pl. 4**).

Chemical characteristics

The chemical characteristics of groundwater from the Woodside confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Woodside 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–5**).

Overthrust Belt
The chemical composition of groundwater in the Woodside confining unit in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs. Individual constituents are listed in **appendix E–5**. Specific conductance measurements (230 and 460 microsiemens per centimeter at 25 degrees Celsius) indicated that both waters were fresh (specific conductance measurements equivalent to TDS concentrations less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the few characteristics and constituents analyzed for in the spring samples, the quality of water from the Woodside confining unit in the OTB 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.

7.3.37 Dinwoody aquifer and confining unit

The physical and chemical characteristics of the Dinwoody aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Dinwoody aquifer and confining unit is composed of the Lower Triassic Dinwoody Formation (**pls. 4**, **5**, and **6**). The Dinwoody Formation consists of basal, middle, and upper units (Kummel, 1954). In Wyoming, the basal and middle units thin eastward from the Overthrust Belt to zero thickness. The 100- to 300-ft thick upper unit consists of interbedded, tan, calcareous siltstone, gray silty limestone, gray crystalline limestone, and a few shale beds. The 25- to 350-ft thick middle unit of the Dinwoody Formation consists of interbedded, gray silty limestone, gray crystalline limestone, and olive-light tan to gray shale beds. The 50- to 175-ft thick basal unit of the Dinwoody Formation consists of light tan to tan, silty limestone and calcareous siltstone.

Permeability in the Dinwoody aquifer and confining unit likely is small on a regional scale, and thus, in most areas the unit probably is capable of yielding only small quantities of water from permeable zones where fractures and secondary permeability are present (Lines and Glass, 1975, Sheet 1; Ahern and others, 1981, Table IV-1). Ahern and others (1981, Figure II-7, and Table IV-1) classified the Dinwoody Formation as an aquitard (confining unit) with locally productive permeable zones in the Overthrust Belt and the adjacent Green River Basin (**Plates 4** and **5**). The investigators (Ahern and others, 1981, Table IV-1) noted that the most productive parts of the Dinwoody Formation were in areas where fractures were present and in interbedded sandstones in the upper part of the formation. In the Wyoming Water Framework Plan, the Dinwoody Formation was classified as a marginal aquifer (WWDC Engineering and others, 2007, Figure 4-9) (**pls. 4**, **5**, and **6**). Because the unit has low overall permeability, but with distinct zones of higher permeability with potential to yield water to wells, the Dinwoody Formation was classified as both an aquifer and confining unit herein (**pls. 4**, **5**, and **6**). Few hydrogeologic data are available describing the Dinwoody aquifer and confining unit in the Snake/Salt River Basin, but two spring-discharge measurements were inventoried as part of this study and are listed on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Dinwoody aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Dinwoody 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–2** and **E–6**).

Northern Ranges
The chemical composition of the Dinwoody aquifer and confining unit in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–2**. The TDS concentration (262 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–2**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Dinwoody aquifer and confining unit in the NR 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.

Star Valley
The chemical composition of the Dinwoody aquifer and confining unit in Star Valley (SV) was characterized and the quality evaluated on the basis of one environmental water sample from

one hot spring. Individual constituents are listed in **appendix E–6**. The TDS concentration (5,250 mg/L) indicated that the water was moderately saline (TDS concentration ranging from 3,000 to 9,999 mg/L) (**appendix E–6**).

Concentrations of some properties and constituents in water from the hot spring issuing from the Dinwoody aquifer and confining unit in SV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for most uses. Concentrations of lead exceeded the USEPA action level of 15 µg/L. Concentrations of one characteristic and two constituents exceeded USEPA aesthetic standards for domestic use: TDS (exceeded SMCL limit of 500 mg/L), chloride (exceeded SMCL limit of 250 mg/L), and sulfate (exceeded SMCL of 250 mg/L). Two characteristics and three constituents approached or exceeded applicable State of Wyoming standards for agricultural use: SAR (exceeded WDEQ Class II standard of 8), TDS (exceeded WDEQ Class II standard of 2,000 mg/L), boron (exceeded WDEQ Class II standard of 750 µg/L), chloride (exceeded WDEQ Class II standard of 100 mg/L), and sulfate (exceeded WDEQ Class II standard of 200 mg/L). One characteristic and one constituent approached or exceeded applicable State of Wyoming livestock water-quality standards: TDS (exceeded WDEQ Class III standard of 2,000 mg/L) and lead (exceeded WDEQ Class III standard of 100 µg/L).

7.4 Paleozoic hydrogeologic units

Paleozoic hydrogeologic units (aquifers and confining units) are described in this section of the report. Lithostratigraphic units of Permian, Pennsylvanian, Mississippian, Devonian, Ordovician, and Cambrian age compose the Paleozoic hydrogeologic units (aquifers and confining units) in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Paleozoic hydrogeologic units underlie Cenozoic and Mesozoic hydrogeologic units in the Snake/Salt River Basin, except in areas where structural deformation has uplifted and exposed the Paleozoic units in the mountains and highlands of the Overthrust Belt. Paleozoic hydrogeologic units are accessible in or very close to these outcrop areas. Depending on location and depth, wells completed in Paleozoic hydrogeologic units produce highly variable quantities and quality of water. The highly complex structural features of the Overthrust Belt require site-specific geologic and hydrogeologic investigation to characterize and develop groundwater resources from Paleozoic hydrogeologic units.

Relatively few water wells are completed in Paleozoic aquifers in the Snake/Salt River Basin, with most along mountain-basin margins where they crop out and are directly exposed at land surface or immediately downgradient in adjacent bordering basins where they occur at shallow depths below younger hydrogeologic units. In these areas, waters are relatively fresh and suitable for most uses. However, permeability decreases and groundwater quality deteriorates rapidly downgradient from outcrop areas along the basin margins. Much of the water used from Paleozoic aquifers in the Snake/Salt River Basin is obtained from springs rather than wells (for example, Star Valley area); many of these springs have moderate to large yields (greater than 100 gal/min).

Paleozoic aquifers produce water from bedrock composed primarily of carbonate rocks [for example, limestone (rock composed of the mineral calcite) and dolostone (rock composed of the mineral dolomite)] and siliciclastic rocks (for example, sandstone) deposited primarily in marine environments. Primary porosity and intergranular permeability are much greater in the sandstones than in the carbonates, where primary permeability is very low. Carbonate aquifers generally may be utilized only in areas where substantial secondary permeability has developed. Permeability of the siliciclastic and carbonate rocks composing the Paleozoic hydrogeologic units may be enhanced by bedding-plane partings, faults, fractures, and solution openings where the rocks have been structurally deformed by folding and faulting in the Overthrust Belt. In fact, development of secondary permeability, such as fractures, faults, and solution openings, in Paleozoic hydrogeologic units usually is required for siting and construction of high yielding springs and wells.

Because data from wells are not available for many Paleozoic hydrogeologic units in the Snake/Salt River Basin, interpretations of the water-bearing properties of some units herein are based on the physical and chemical hydrogeologic characteristics of the same or similar units in other parts of Wyoming. Permeability and groundwater circulation in Paleozoic hydrogeologic units has been studied at many locations in Wyoming, and they are controlled by lithology, sedimentary structure and depositional environment, and tectonic structures such as folds and faults (for example, Lundy, 1978; Huntoon and Lundy, 1979; Thompson, 1979; Eisen and others, 1980; Richter, 1981; Western Water Consultants, Inc., 1982, 1993, 1995; Cooley, 1984, 1986; Davis, 1984; Huntoon, 1985, 1993; Jarvis, 1986; Spencer, 1986; Mills, 1989; Mills and Huntoon, 1989; Wiersma, 1989; Blanchard, 1990; Blanchard and others, 1990; Younus, 1992; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Except near outcrops, where water-table (unconfined) conditions may be encountered, groundwater in Paleozoic hydrogeologic units is generally semiconfined or confined.

Recharge to Paleozoic hydrogeologic units generally occurs where the units crop out, although severing by faults near recharge areas may disrupt downgradient 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 springs are developed and most wells are completed. Elsewhere, and with increasing depth and as the water moves away from the outcrop, the water can have high TDS, limiting the use of water for most purposes.

7.4.1 Phosphoria aquifer and confining unit

The physical and chemical characteristics of the Phosphoria aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Phosphoria aquifer and confining unit is composed of the Permian Phosphoria Formation (**pls. 4**, **5**, and **6**). The Phosphoria aquifer and confining unit is overlain by the Dinwoody aquifer and confining unit and underlain by the Wells or Tensleep aquifer in most of the Snake/Salt River Basin (**pls. 4**, **5**, and **6**). The Phosphoria Formation consists of an upper part of dark to light gray, cherty shale and sandstone, and a lower part of brown-weathering, dark, phosphatic shale and limestone (Rubey and others, 1980; Love and others, 1992).
The formation is divided into two members at some locations (individual members not shown on Plates 4, 5 and 6). The Rex Chert Member is composed of dark gray siltstone, black, thin-bedded chert and limestone, and a few thin beds of phosphate rock in the upper part. Resistant ledges of gray, cherty, dolomitic limestone and some bedded chert are present in the middle and lower part of the Rex Chert Member (Rubey and others, 1980). The Meade Peak Member consists of dark gray, non-resistant, and brown phosphatic siltstone and cherty siltstone, gray dolomite, several blue beds of phosphorite, and one bed of vanadium-bearing carbonaceous siltstone (Rubey and others, 1980).

Phosphoria Formation thickness varies by geographic area in the Snake/Salt River Basin. Thickness of the Phosphoria Formation decreases eastward in the Overthrust Belt and ranges from about 180 to 361 ft (Love and Love, 1978; Oriel and Platt, 1980; Oriel and Moore, 1985; Rubey and others, 1980; Love and others, 1992; Love and Love, 2000). Thickness of the Phosphoria Formation in the Teton Range ranges from 180 to 220 ft (Love, 1974a,b, 2003a; Christiansen and others, 1978; Oriel and Moore, 1985; Love and Love, 2000). Thickness of the Phosphoria Formation in the Gros Ventre Range ranges from about 180 to about 235 ft (Love and Love, 1978, 2000; Oriel and Platt, 1980; Rubey and others, 1980; Love and others, 1992; Love, 2001b,c; Love and Reed, 2001a).

The Phosphoria Formation is classified as an aquifer, confining unit, or both by previous investigators (**pls. 4**, **5**, and **6**). Robinove and Berry (1963, p. V18) identified the Phosphoria Formation and the underlying Wells Formation as potential Paleozoic aquifers in the Bear River valley to the south of the Snake/Salt River Basin; the investigators noted that both formations "may be expected to yield small to moderate amounts of water to wells." Primary permeability in the Phosphoria aquifer likely is small, and in most areas the unit probably is capable of yielding only "small quantities" of water (Lines and Glass, 1975, Sheet 1). However, in areas where fractures are present and secondary permeability is developed, the aquifer is capable of yielding "moderate quantities" of water (Lines and Glass, 1975, Sheet 1). Ahern and others (1981, Figure II-7, and Table IV-1) classified the Phosphoria Formation as a locally confining minor aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators (Ahern and others, 1981, Table IV-1) noted that the most productive parts of the Phosphoria Formation were in areas where fractures were present and in interbedded sandstones in the upper part of the formation. In the Wyoming Water Framework Plan, the Phosphoria Formation was classified as a minor aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4**, **5**, and **6**). Hydrogeologic data describing the Phosphoria aquifer and confining unit, including spring-discharge and well-yield measurements and other hydraulic properties, are summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Phosphoria aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Phosphoria 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–2** and **E–5**).

Northern Ranges

The chemical composition of the Phosphoria aquifer and confining unit in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituents are listed in **appendix E–2**. Major-ion composition in relation to TDS concentrations for springs issuing from the Phosphoria aquifer and confining unit is shown on a trilinear diagram (**appendix F–2, diagram E**). The TDS concentrations for the springs ranged from 95.4 to 164 mg/L, with a median of 119 mg/L, indicating that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram E**). On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Phosphoria aquifer and confining unit in the NR 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.

Overthrust Belt

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–5**. The specific conductance measured in the spring (320 microsiemens per centimeter at 25 degrees Celsius) indicated that the water was fresh (measured specific conductance equivalent to TDS concentration less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for in the spring sample, the quality of water from the Phosphoria aquifer and confining unit in the OTB 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.

7.4.2 Quadrant Sandstone

Within the Snake/Salt River Basin, the Pennsylvanian Quadrant Sandstone (also known

as the Quadrant Quartzite) is present only in the Yellowstone Volcanic Area (**pl. 1; pl. 6**), and consists of well-bedded white to pink, fine-to medium-grained quartzite (Mallory, 1967). The Quadrant Sandstone is laterally equivalent to the Tensleep Sandstone. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic unit in the Snake/Salt River Basin.

7.4.3 Tensleep aquifer

The physical and chemical characteristics of the Tensleep aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Tensleep aquifer is composed of saturated and permeable parts of the Middle to Upper Pennsylvanian to Permian Tensleep Sandstone (**pls. 5** and **6**). The Tensleep Sandstone consists of light-gray, weathering yellowish brown, fine-grained hard brittle sandstone; some zones are quartzitic (Love and others, 1992). The middle and lower parts of the formation contain many beds of gray, hard fine-grained limestone and dolomite. The Tensleep Sandstone is transitional with the underlying Amsden Formation. The Tensleep Sandstone is stratigraphically equivalent to the Wells Formation—the lithostratigraphic unit is identified as the Wells Formation south and west of the Jackson thrust fault and as the Tensleep Sandstone north and east of the Jackson thrust fault (Love and others, 1992). Thickness of the Tensleep Sandstone ranges from about 385 to about 450 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972, 1987; Jobin, 1972; Love, 1974a,b, 1975b, 2001a,b,c, 2003a; Christiansen and others, 1978; Love and Love, 1978; Oriel and Moore, 1985; Love and others, 1992).

The Tensleep aquifer is overlain by the Phosphoria aquifer and confining unit and underlain by the Amsden aquifer (**pls. 5** and **6**). In the eastern Gros Ventre Range, the Tensleep aquifer is confined from above by the Phosphoria-Dinwoody-Chugwater confining unit (composed of most of the Phosphoria Formation and the Dinwoody and Chugwater Formations) and from below by the Amsden confining unit composed of the Amsden Formation (Mills, 1989; Mills and Huntoon, 1989) (**pl. 5**). In addition, the Tensleep aquifer in the eastern Gros Ventre Range also is composed of hydraulically connected lower sandstones in the overlying Phosphoria Formation (Mills, 1989; Mills and Huntoon, 1989) (**pl. 5**).

The Tensleep Sandstone is classified as an aquifer by all investigators and that definition is retained herein (**pls. 5** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Tensleep Sandstone was a poor to good aquifer in the Snake/Salt River Basin (**pls. 5** and **6**). Ahern and others (1981, Figure II-7, and Table IV-1) classified the Tensleep Sandstone and the equivalent Wells Formation as major aquifers in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators also considered the Wells/Tensleep aquifer to be part of a larger regional Paleozoic aquifer system composed of many different hydrogeologic units (**pls. 4** and **5**). Mills (1989) and Mills and Huntoon (1989) classified the formation as an aquifer in the eastern Gros Ventre Range (**pl. 5**). In the Wyoming Water Framework Plan, the Wells Formation was classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**).

Lines and Glass (1975, Sheet 1) noted that sandstone beds composing the Tensleep Sandstone were aquifers capable of yielding moderate to large quantities of water (100 gal/min or more), depending upon local recharge, sandstone bed continuity, and development of secondary permeability from fractures. In addition, the investigators (Lines and Glass, 1975, Sheet 1) noted that sandstone beds "on topographic highs may be drained [unsaturated], especially if underlying limestones have extensive solution development." Several investigators (Cox, 1976; Mills, 1989; Mills and Huntoon, 1989) reported yields as much as 100 gal/min or more to individual springs in the Gros Ventre Range. Mills (1989) and Mills and Huntoon (1989) noted that permeability in lithologic units composing the aquifer in the eastern Gros Ventre Range was both primary and secondary. Permeability in sandstones

in the Tensleep aquifer was determined to be intergranular along the backlimbs of examined folds, but could be secondarily enhanced due to fractures and associated piping along the forelimbs of examined folds (Mills, 1989; Mills and Huntoon, 1989). Primary permeability of dolomite in the Tensleep aquifer was small along the forelimbs of examined folds, but was enhanced due to fracturing and karstification along the forelimbs of examined folds.

Hydrogeologic information describing the Tensleep aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **plate 3**. Spring-discharge measurements and well yields inventoried as part of this study (**pl. 3**) confirm that sandstone aquifers in the Tensleep Sandstone are capable of yielding moderate to large quantities of water (100 gal/min or more) in parts of the Snake/Salt River Basin.

Chemical characteristics

The chemical characteristics of groundwater from the Tensleep aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Tensleep 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–2** and **E–4**).

Northern Ranges

The chemical composition of the Tensleep aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water sample from as many as six springs. Summary statistics calculated for available constituents are listed in **appendix E–2**. Major-ion composition in relation to TDS concentrations for springs issuing from the Tensleep aquifer is shown on a trilinear diagram (**appendix F–2, diagram F**). TDS concentrations indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram F**). The TDS concentrations for the springs ranged from 123 to 312 mg/L, with a median of 268 mg/L. On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Tensleep aquifer in the NR 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.

Jackson Hole

The chemical composition of the Tensleep aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one produced water sample from one well. The TDS concentration (1,980 mg/L) indicated that the water was slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L). The pH value in the produced water sample was 7.2. Measured concentrations of cations were 468 mg/L (sodium), 190 mg/L (calcium), and 27 mg/L (magnesium). Measured concentrations of anions were 854 mg/L (sulfate), 684 mg/L (bicarbonate), and 110 mg/L (chloride).

Concentrations of some properties and constituents in water from the Tensleep aquifer in the JH produced water sample approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: TDS (exceeded SMCL limit of 500 mg/L) and sulfate (exceeded SMCL of 250 mg/L). Two constituents in the produced water sample approached or exceeded applicable State of Wyoming standards for agricultural-use standards: chloride (exceeded WDEQ Class II standard of 100 mg/L) and sulfate (exceeded WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Green River and Hoback Basins

The chemical composition of the Tensleep aquifer in the Green River and Hoback Basins (GH) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are

listed in **appendix E–4**. The TDS concentration (303 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–4**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Tensleep aquifer in the GH 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.

7.4.4 Wells aquifer

The physical and chemical characteristics of the Wells aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Wells aquifer is composed of the Middle to Upper Pennsylvanian to Permian Wells Formation (**pl. 4**). The Wells Formation consists of interbedded gray limestone and pale yellow calcareous sandstone with minor gray dolomite beds; the lower part of the formation is cherty (Love and others, 1992). The Wells Formation is stratigraphically equivalent to the Tensleep Sandstone—the lithostratigraphic unit is identified as the Wells Formation south and west of the Jackson thrust fault and as the Tensleep Sandstone north and east of the Jackson thrust fault (Love and others, 1992). Thickness of the Wells Formation in the Overthrust Belt ranges from about 591 to about 1,969 ft (Jobin, 1965, 1972; Pampeyan and others, 1967; Albee, 1968, 1973; Schroeder, 1973, 1974, 1976, 1979, 1981, 1987; Love and Love, 1978; Oriel and Platt, 1980; Oriel and Moore, 1985; Schroeder and others, 1981; Love and others, 1992).

The Wells Formation is classified as an aquifer by most investigators and that definition is retained herein (**pl. 4**). Berry (1955) identified the Wells Formation (referred to as the Tensleep Sandstone) as a potential aquifer (**pl. 4**) in the Cokeville area to the south of the Snake/Salt River Basin in the Overthrust Belt. Robinove and Berry (1963, p. V18) identified the Wells Formation and overlying Phosphoria Formation as potential Paleozoic aquifers in the Bear River valley to the south of the Snake/Salt River Basin in the Overthrust Belt; the investigators noted that both formations "may be expected to yield small to moderate amounts of water to wells." Similarly, Lines and Glass (1975, Sheet 1) noted that sandstone beds composing the formation were aquifers capable of yielding moderate to large quantities of water, depending upon local recharge, sandstone bed continuity, and development of secondary permeability from fractures. In addition, the investigators (Lines and Glass, 1975, Sheet 1) noted that sandstone beds "on topographic highs may be drained, especially if underlying limestones have extensive solution development." Cox (1976, Sheet 1) speculated that sandstones in the formation might yield a few tens of gallons per minute per well. Ahern and others (1981, Figure II-7, and Table IV-1) classified the Wells Formation and the equivalent Tensleep Sandstone as major aquifers in the Overthrust Belt and adjacent Green River Basin (**pl. 4**). In the Wyoming Water Framework Plan, the Wells Formation was classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pl. 4**). Hydrogeologic information describing the Wells aquifer, including well-yield and spring-discharge measurements and other hydraulic characteristics, is summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Wells aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Wells 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–5**).

Overthrust Belt

The chemical composition of groundwater in the Wells aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as 12 springs and 1 well. Summary statistics calculated for available constituents are listed in

appendix E–5. Major ion composition in relation to TDS for springs issuing from the Wells aquifer is shown on a trilinear diagram (**appendix F–5, diagram I**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram I**). The TDS concentrations for the springs ranged from 114 to 239 mg/L, with a median of 171 mg/L. The TDS concentration for the well was 317 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Wells aquifer in the OTB 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.

7.4.5 Amsden aquifer

The physical and chemical characteristics of the Amsden aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Amsden aquifer is composed of saturated and permeable parts of the Upper Mississippian to Pennsylvanian Amsden Formation (**pls. 4, 5,** and **6**). The Amsden Formation consists of red and gray cherty limestone and yellow siltstone, sandstone, and conglomerate (Mallory, 1967; Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980; Love and others, 1992; and M'Gonigle and Dover, 1992). The Amsden Formation overlies the Madison Group or Limestone north and east of the Jackson thrust fault and is overlain by the stratigraphically equivalent Wells Formation south and west of the Jackson thrust fault. The Amsden Formation has as many as three members in the Snake/Salt River Basin: Ranchester Limestone Member (Pennsylvanian); Horseshoe Shale Member (Upper Mississippian to Lower Pennsylvanian); and Darwin Sandstone Limestone Member (Upper Mississippian) (Mallory, 1967).

Thickness of the Amsden Formation varies by geographic area in the Snake/Salt River Basin. Thickness of the Amsden Formation in the Gros Ventre Range is about 400 to 450 ft (Love and Reed, 2000, 2001a,b; Love, 2001a,c, 2003c; Love and others, 1992). Thickness of the Amsden Formation in the Teton Range ranges from 230 to 700 ft (Schroeder, 1972; Love, 1974a,b, 2003a; Christiansen and others, 1978; Oriel and Moore, 1985). Thickness of the Amsden Formation in the Overthrust Belt ranges from about 328 to about 700 ft (Oriel and Platt, 1980; Love and others, 1992).

The Amsden Formation in the Snake/Salt River Basin is classified as either an aquifer or confining unit by previous investigators, depending upon the physical characteristics of the unit in the area examined (**pls. 4, 5,** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Amsden Formation was a fair to poor aquifer in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Lines and Glass (1975, Sheet 1) noted that small quantities of water might be available from cherty limestone in the formation in the Overthrust Belt, but "on topographic highs, the Amsden Formation is probably well-drained, especially if underlying limestones have extensive solution development." Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a minor locally confining aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators also considered the Amsden aquifer to be part of a larger regional Paleozoic aquifer system composed of many different hydrogeologic units (**pls. 4** and **5**). In the eastern Gros Ventre Range and the Salt River Range, general permeability of the shale and limestone composing much of the Amsden Formation is small enough that the lithostratigraphic unit is considered a confining unit that overlies the Madison aquifer, and underlies the Tensleep aquifer (Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990) (**pls. 4** and **5**). However, the investigators noted that sandstones in the Amsden Formation were permeable and that sandstone permeability was intergranular. In the Wyoming Water Framework Plan, the Amsden Formation was classified as a marginal aquifer throughout Wyoming (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Amsden Formation in the adjacent Green

River Basin and surrounding areas have classified the formation as an aquifer (Ahern and others, 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein). In the upper Colorado River Basin and adjacent areas (including Green River Basin and parts of the Overthrust Belt), Geldon (2003) classified the Ranchester Limestone and the Darwin Sandstone Members as aquifers and the Horseshoe Shale Member as a confining unit (see Bartos and Hallberg, 2010, Figure 5-4). Hydrogeologic information describing the Amsden aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **plate 3**.

Chemical characteristics

The chemical characteristics of groundwater from the Amsden aquifer in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Amsden 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–2, E–3,** and **E–5**).

Northern Ranges
The chemical composition of the Amsden aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–2**. The TDS concentration (56.3 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–2**). On the basis of the characteristics and constituents analyzed for in the one spring sample, the quality of water from the Amsden aquifer in the NR 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.

Jackson Hole
The chemical composition of the Amsden aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituents are listed in **appendix E–3**. The TDS concentration (327 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for in the one sample, the quality of water from the Amsden aquifer in JH was suitable for most uses, although the concentration of one constituent exceeded health-based standards: radon (the 1 sample analyzed for this constituent exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

Overthrust Belt
The chemical composition of groundwater in the Amsden aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituents are listed in **appendix E–5**. Major ion composition in relation to TDS for springs issuing from the Amsden aquifer is shown on a trilinear diagram (**appendix F–5, diagram J**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram J**). The TDS concentrations for the springs ranged from 119 to 178 mg/L, with a median of 138 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Amsden aquifer in the OTB 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.

7.4.6 Madison aquifer

The physical and chemical characteristics of the Madison aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Lower to Upper Mississippian Madison Limestone is a thick sequence of carbonate rocks

[limestone (carbonate rock composed of the mineral calcite) and dolostone (carbonate rock composed of the mineral dolomite)] that consists of two parts—an upper part of light- to dark-gray, thick-bedded to massive limestone, and a lower part of dark gray, thin-bedded limestone and dolomite (Lines and Glass, 1975; Oriel and Platt, 1980; Love and others, 1992). In the vicinity of Grand Teton National Park, thin lenses of brown cherty dolomite are present near the base and lenses of black chert are common (Love and others, 1992). Thickness of the Madison Limestone in the Gros Ventre and Teton Ranges ranges from about 1,100 to 1,500 ft (Love and Love, 1978; Oriel and Platt, 1980; Love and others, 1992). Thickness of the Madison Group or Limestone in the Overthrust Belt ranges from about 800 to about 1,800 ft (Oriel and Platt, 1980; Schroeder, 1974, 1976, 1979, 1981, 1987; Schroeder and others, 1981; Lageson, 1986).

Saturated and permeable parts of the Madison Group or Limestone compose the Madison aquifer. The Madison Group or Limestone in the Snake/Salt River Basin is classified as an aquifer by all previous investigators (**pls. 4, 5,** and **6**). The Madison aquifer is overlain by the Amsden aquifer and underlain by the Darby aquifer (**pls. 4, 5,** and **6**). In the eastern Gros Ventre Range and the Salt River Range, the Madison aquifer is part of different aquifer systems composed of other Paleozoic aquifers with varying degrees of hydraulic connection (Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990) (**pls. 4** and **5**).

Primary permeability (intergranular or intercrystalline) of the Madison Group or Limestone generally is low, and large volumes of the formation are composed of relatively impermeable rocks (for example, Mills, 1989; Mills and Huntoon, 1989). The availability of water from the Madison aquifer depends substantially on the development of secondary permeability, primarily fractures and karstic features such as solution openings. Where permeability has been enhanced by fracturing and solution openings, the Madison Group or Limestone is one of the most productive aquifers in the Snake/Salt River Basin (**pl. 3**), as well as in many other areas of Wyoming (for example, Bartos and others, 2012, and references therein).

In areas where secondary permeability is developed, springs issuing from and wells completed in the Madison aquifer may yield several hundred gallons per minute (Lines and Glass, 1975; Cox, 1976; Huntoon and Coogan, 1987; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990; Sunrise Engineering, 2003, 2009) (**pl. 3**). Some of these springs issuing from the Madison aquifer are used to provide water for public-supply purposes in the Snake/Salt River Basin [notably, Periodic Spring is used to provide a substantial amount of the water supply for the city of Afton (Huntoon and Coogan, 1987, and references therein; Forsgren Associates, 1990; Sunrise Engineering, 2009)]. Fracturing of rocks composing the Madison Group or Limestone (and other Paleozoic hydrogeologic units) generally occurs in areas of structural deformation such as near faults and on the limbs of folds (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990; Rendezvous Engineering, PC, and Hinckley Consulting, 2009). Solution openings generally develop in outcrop areas or near land surface where recharging waters containing carbon dioxide dissolve parts of the aquifer until eventually discharging from the aquifer (Lines and Glass, 1975; Cox, 1976; Huntoon and Coogan, 1987; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990). Fracturing and faulting provides a pathway for vertical movement of groundwater between different Paleozoic aquifers (including the Madison aquifer) at some locations in the Snake/Salt River Basin (Mills, 1989; Mills and Huntoon, 1989).

In the Snake/Salt River Basin, much of the water discharged from the Madison aquifer and other Paleozoic aquifers is through a few large springs where there has been selective enlargement of solution openings and a concentration of flow in a few of the larger openings (Lines and Glass, 1975; Cox, 1976; Huntoon and Coogan, 1987; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990). Outcrops

on topographic highs commonly are unsaturated (drained) to depths of several hundred feet. Lines and Glass (1976, Sheet 1) noted that wells that penetrated "water-bearing solution channels" were likely to "yield much more water than wells that do not penetrate the major conduits." Unlike limestones in other Paleozoic hydrogeologic units of the Snake/Salt River Basin, outcrops of the Madison Group or Limestone have ancient karstic features such as solution openings that probably developed before and during deposition of the overlying Amsden Formation (Lines and Glass, 1975; Mills, 1989; Mills and Huntoon, 1989). Consequently, solution permeability in the Madison aquifer probably is present at greater depths below the present land surface than in other Paleozoic hydrogeologic units.

Recharge to the Madison aquifer is from direct infiltration of precipitation (snowmelt and rain), snowmelt runoff, lakes, and ephemeral and perennial streamflow losses on outcrops (Lines and Glass, 1975; Cox, 1976; Huntoon and Coogan, 1987; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990). This recharge may be enhanced in areas where fractures occur along the axes of anticlines or in karstified areas (Huntoon and Coogan, 1987; Mills, 1989; Mills and Huntoon, 1989; Blanchard, 1990; Blanchard and others, 1990). Discharge from the Madison aquifer occurs from withdrawals by pumped wells and naturally by evapotranspiration, gaining streams, seeps, and spring flows. Hydrogeologic data describing the Madison aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Madison aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Madison 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–1** to **E–6**).

Yellowstone Volcanic Area

The chemical composition of the Madison aquifer in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of environmental water samples from one spring and two wells. Individual constituents are listed in **appendix E–1**. TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–1**). The TDS concentration in the spring was 245 mg/L. The TDS concentrations for the wells were 128 and 138 mg/L. On the basis of the characteristics and constituents analyzed for in the spring and well samples, the quality of water from the Madison aquifer in the YVA 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.

The chemical composition of Madison aquifer in the YVA also was characterized and the quality evaluated on the basis of environmental water samples from as many as three hot springs. Individual constituents are listed in **appendix E–1**. Major ion composition in relation to TDS for the three hot springs issuing from the Madison aquifer in the YVA is shown on a trilinear diagram (**appendix F–1, diagram G**). TDS concentrations indicated that waters ranged from slightly saline (2 of 3 samples, TDS concentrations between 1,000 to 2,999 mg/L) to fresh (1 of 3 samples, TDS concentration less than or equal to 999 mg/L) (**appendix E–1; appendix F–1, diagram G**). TDS concentrations for the hot springs ranged from 695 to 1,960 mg/L, with a median of 1,550 mg/L.

Concentrations of some properties and constituents in water from the three hot springs issuing from the Madison aquifer in the YVA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of two constituents exceeded health-based standards: boron (all 3 samples exceeded the WDEQ Class II standard of 750 µg/L) and fluoride (1 of 3 samples exceeded the USEPA MCL of 4 mg/L). Concentrations of

one characteristic and two constituents exceeded USEPA aesthetic standards for domestic use: TDS (all 3 samples exceeded the SMCL of 500 mg/L), fluoride (all 3 samples exceeded the SMCL of 2 mg/L), and sulfate (2 of 3 samples exceeded the SMCL of 250 mg/L).

Concentrations of some characteristics and constituents in water from the three hot springs issuing from the Madison aquifer in the YVA exceeded State of Wyoming standards for agricultural and livestock use. Three constituents were measured at concentrations greater than agricultural-use standards: boron (all 3 samples exceeded the WDEQ Class II standard of 750 µg/L), chloride (all 3 samples exceeded the WDEQ Class II standard of 100 mg/L), and sulfate (2 of 3 samples exceeded the WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Northern Ranges

The chemical composition of the Madison aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as five springs and one cave. Summary statistics calculated for available constituents in the five springs and one cave sample are listed in **appendix E–2** (one cave sample grouped with five spring samples for summary purposes in **appendix E–2**). Major ion composition in relation to TDS for the springs issuing from the Madison aquifer in the NR is shown on a trilinear diagram (**appendix F–2, diagram G**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram G**). The TDS concentrations for the springs and cave ranged from 31.5 to 106 mg/L, with a median of 89.0 mg/L. The TDS concentration in water issuing from the cave was less than 83 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Madison aquifer in the NR 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.

Jackson Hole

The chemical composition of the Madison aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of environmental water samples from as many as six springs and one well. Summary statistics calculated for available constituents are listed in **appendix E–3**. Major ion composition in relation to TDS for the springs issuing from the Madison aquifer in JH is shown on a trilinear diagram (**appendix F–3, diagram I**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–3; Appendix F–3, diagram I**). The TDS concentrations for the springs ranged from 127 to 588 mg/L, with a median of 273 mg/L. The TDS concentration in the well was 262 mg/L.

Concentrations of some properties and constituents in water from the Madison aquifer in JH approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of one characteristic and one constituent in one of the six spring samples exceeded USEPA aesthetic standards for domestic use: TDS (exceeded SMCL limit of 500 mg/L) and sulfate (exceeded SMCL of 250 mg/L). One constituent in one of the six spring samples approached or exceeded applicable State of Wyoming standards for agricultural-use standards: sulfate (exceeded WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

On the basis of the characteristics and constituents analyzed for, the quality of water from the Madison aquifer in wells and springs in JH was suitable for most uses, as no concentrations of constituents exceeded health-based standards. No characteristics or constituents in the well sample approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Green River and Hoback Basins

The chemical composition of the Madison aquifer in the Green River and Hoback Basins (GH) was

characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **appendix E–4**. The TDS concentrations (94.6 and 102 mg/L) indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–4**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Madison aquifer in the GH 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.

Overthrust Belt

The chemical composition of groundwater in the Madison aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as 18 springs, 2 wells, and 1 hot spring. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major ion composition in relation to TDS for the 18 springs issuing from the Madison aquifer in the OTB is shown on a trilinear diagram (**appendix F–5, diagram K**). TDS concentrations indicated that waters in all 18 springs (**appendix F–5, diagram K)** and one of two wells were fresh (TDS concentrations less than or equal to 999 mg/L), and waters from the hot spring and one of two wells were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**appendix E–5**). The TDS concentrations for the 18 springs ranged from 89.0 to 319 mg/L, with a median of 194 mg/L. The TDS concentrations for the wells were 110 and 1,150 mg/L. The TDS concentration in the hot spring was 1,160 mg/L.

On the basis of the characteristics and constituents analyzed for in the 18 spring samples, the quality of water from the Madison aquifer in the OTB 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.

Concentrations of some properties and constituents in water from the two wells and the hot spring in the Madison aquifer in the OTB 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 USEPA aesthetic standards for domestic use in one of the two well samples and in the hot spring sample: TDS (exceeded the SMCL of 500 mg/L) and sulfate (exceeded the SMCL of 250 mg/L). One constituent approached or exceeded applicable State of Wyoming standards for agricultural-use standards in one of the two well samples and in the hot spring sample: sulfate (exceeded the WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards in samples from the two wells or the hot spring.

The chemical composition of the Madison aquifer in the OTB also was characterized and the quality evaluated on the basis of one produced water sample from one well. The TDS concentration (5,600 mg/L) indicated that the water was moderately saline (TDS concentration ranging from 3,000 to 9,999 mg/L). The pH value in the produced water sample was 8.5. Measured concentrations of cations were 1,780 mg/L (sodium), 151 mg/L (calcium), 54 mg/L (magnesium), and 25 mg/L (potassium). Measured concentrations of anions were 2,200 mg/L (sulfate), 1,870 mg/L (bicarbonate), and 440 mg/L (chloride).

Concentrations of some properties and constituents in the produced water sample from the Madison aquifer in the OTB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for most uses. Concentrations of one characteristic and two constituents exceeded USEPA aesthetic standards for domestic use and State of Wyoming standards for agricultural use: TDS (exceeded SMCL limit of 500 mg/L and WDEQ Class II standard of 2,000 mg/L), chloride (exceeded SMCL of 250 mg/L and WDEQ Class II standard of 100 mg/L), and sulfate (exceeded SMCL of 250 mg/L and WDEQ Class II standard of 200

mg/L). One characteristic approached or exceeded applicable State of Wyoming livestock water-quality standards: TDS (exceeded WDEQ Class III standard of 5,000 mg/L).

Star Valley
The chemical composition of the Madison aquifer in Star Valley (SV) 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 E–6**. Major ion composition in relation to TDS for the wells in the Madison aquifer in the SV is shown on a trilinear diagram (**appendix F–6, diagram C**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–6**). TDS concentrations for the wells ranged from 244 to 349 mg/L, with a median of 311 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Madison aquifer in SV 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.

The chemical composition of a Paleozoic limestone (may be Madison aquifer) underlying the Salt Lake Formation in Star Valley (SV) was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituents are listed in **appendix E–6**. The TDS concentration (169 mg/L) from one well indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–6**). On the basis of the characteristics and constituents analyzed for, the quality of water from a Paleozoic limestone aquifer in SV 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.

7.4.7 Three Forks and Jefferson Formations

Within the Snake/Salt River Basin, the Upper Devonian Three Forks Formation is present only in the Yellowstone Volcanic area (**pl. 1; pl. 6**) and consists of pink, yellow, and green, dolomitic siltstone and shale (Love and Christiansen, 1985, Sheet 2). Within the Snake/Salt River Basin, the Upper Devonian Jefferson Formation also is present only in the Yellowstone Volcanic Area (**pl. 1; pl. 6**) and consists of massive siliceous dolomite and limestone (Love and Christiansen, 1985, Sheet 2). Cox (1976, Sheet 1) speculated that wells completed in either formation probably would not yield more than a few gallons per minute. No data were located describing the physical and chemical hydrogeologic characteristics of either lithostratigraphic unit in the Snake/Salt River Basin.

7.4.8 Darby aquifer

The physical and chemical characteristics of the Darby aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Darby aquifer is composed of saturated and permeable parts of the Upper Devonian to Lower Mississippian Darby Formation (**pls. 4, 5,** and **6**). The Darby Formation consists of an upper part of dull-yellow, gray, pink, and black thin-bedded dolomitic siltstone and shale, and a lower part of brown, vuggy, siliceous, brittle dolomite containing sparse thin limestone beds and thin sandstone beds (Love and others, 1992).

Thickness of the Darby Formation varies by geographic area in the Snake/Salt River Basin. Thickness of the Darby Formation in the Gros Ventre Range ranges from about 285 to 450 ft (Love and others, 1992). Thickness of the Darby Formation in Jackson Hole is about 250 ft (Love, 2003b). Thickness of the Darby Formation in the Teton Range ranges from about 250 to 450 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972; Christiansen and others, 1978; Love and others, 1992). Thickness of the Darby Formation in the Overthrust Belt ranges from about 285 to 700 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972, 1973, 1974, 1976, 1981, 1987; Jobin, 1972; Albee, 1973; Albee and Cullins, 1975; Oriel

and Platt, 1980; Schroeder and others, 1981; Lageson, 1986; Love and others, 1992; Love and Love, 2000; Love, 2003c).

The Darby Formation in the Snake/Salt River Basin is classified as an aquifer by previous investigators (**pls. 4, 5,** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Darby Formation was a fair to poor aquifer in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Lines and Glass (1976, Sheet 1) speculated that the Darby Formation probably would not yield more than a few gallons per minute per well. Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators also considered the Darby aquifer to be part of a larger regional Paleozoic aquifer system composed of many different Paleozoic hydrogeologic units (**pls. 4** and **5**). In the eastern Gros Ventre Range and the Salt River Range, the Darby Formation is classified as an aquifer and is considered part of an aquifer system composed of other Paleozoic hydrogeologic units with varying amounts of hydraulic connection (**pls. 4** and **5**). In the Wyoming Water Framework Plan, the Darby Formation was classified as a major aquifer throughout Wyoming (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Darby Formation in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer or confining unit (Ahern and others, 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein). In the upper Colorado River Basin and adjacent areas (including Green River Basin, and parts of the Overthrust Belt), Geldon (2003) classified the Darby Formation as a regional confining unit (see Bartos and Hallberg, 2010, Figure 5-4). In the Wind River and Bighorn Basins east of the Snake/Salt River Basin, the Darby Formation was classified as an aquifer (**pl. 6**) (Bartos and others, 2012, and references therein). Permeability of the dolomite that comprises much of the Darby Formation in the eastern Gros Ventre Range primarily is intercrystalline (Mills, 1989; Mills and Huntoon, 1989). Spring-discharge measurements for the Darby aquifer in the Snake/Salt River Basin are summarized on **plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Darby aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Darby 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–1** and **E–5**).

Yellowstone Volcanic Area

The chemical composition of the Darby aquifer in the Yellowstone Volcanic Area (YVA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituents are listed in **appendix E–1**. The TDS concentration (183 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–1**). On the basis of the characteristics and constituents analyzed for, the quality of water from the Darby aquifer in the YVA 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.

Overthrust Belt

The chemical composition of groundwater in the Darby aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as four springs. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major ion composition in relation to TDS for springs issuing from the Darby aquifer in the OTB is shown on a trilinear diagram (**appendix F–5, diagram L**). TDS concentrations indicated that waters from two of the four springs were fresh (TDS concentrations less than or equal to 999 mg/L), and waters from the other two springs were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**appendix E–5; appendix F–5, diagram L**). The TDS concentrations for the springs ranged from 134 to 1,330 mg/L, with a median of 719 mg/L.

Concentrations of some properties and constituents in water from springs issuing from the Darby aquifer in the OTB 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 USEPA aesthetic standards for domestic use in two of the four spring samples: TDS (exceeded the SMCL of 500 mg/L) and sulfate (exceeded the SMCL of 250 mg/L). One constituent (sulfate) approached or exceeded the applicable State of Wyoming standard for agricultural use (two of the four springs exceeded the WDEQ Class II standard of 200 mg/L). No characteristics or constituents measured in springs issuing from the Darby aquifer approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.4.9 Bighorn aquifer

The physical and chemical characteristics of the Bighorn aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Bighorn aquifer is composed of saturated and permeable parts of the Upper Ordovician Bighorn Dolomite (**pls. 4, 5,** and **6**). The Bighorn Dolomite consists of gray massive dolomite and dolomitic limestone (Love and others, 1992). Thickness of the Bighorn Dolomite varies by geographic area in the Snake/Salt River Basin. Thickness of the Bighorn Dolomite in the Gros Ventre Range ranges from about 200 to 500 ft (Love and others, 1992). Thickness of the Bighorn Dolomite in the Teton Range ranges from about 400 to 440 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972; Christiansen and others, 1978; Oriel and Moore, 1985; Love and others, 1992). Thickness of the Bighorn Dolomite in the Overthrust Belt ranges from about 400 to 820 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972, 1973, 1976, 1979; Jobin, 1972; Albee and Cullins, 1975; Oriel and Platt, 1980; Oriel and Moore, 1985; Lageson, 1986; Love and others, 1992; Love and Love, 2000; Love, 2003c).

The Bighorn Dolomite is classified as an aquifer by previous investigators (**pls. 4, 5,** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Bighorn Dolomite was a fair to poor aquifer in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators also considered the Bighorn aquifer to be part of a larger regional Paleozoic aquifer system composed of many different Paleozoic hydrogeologic units (**pls. 4** and **5**). In the eastern Gros Ventre Range and the Salt River Range, the Bighorn Dolomite is classified as an aquifer and is considered part of an aquifer system composed of other Paleozoic hydrogeologic units with varying amounts of hydraulic connection (**pls. 4** and **5**). In the Wyoming Water Framework Plan, the Bighorn Dolomite was classified as a major aquifer throughout Wyoming (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Bighorn Dolomite in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer or confining unit (Ahern and others, 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein). In the upper Colorado River Basin and adjacent areas (including Green River Basin, and parts of the Overthrust Belt), Geldon (2003) classified the Bighorn Dolomite as a regional confining unit (see Bartos and Hallberg, 2010, Figure 5-4). In the Wind River and Bighorn Basins east of the Snake/Salt River Basin, the Bighorn Dolomite was classified as an aquifer (**pl. 6**) (Bartos and others, 2012, and references therein).

Permeability of the dolomite that composes much of the Bighorn aquifer is both primary (intercrystalline) and secondary (fractures and solution openings) (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Large spring discharges (100 gal/min or more) inventoried as part of this study (**pl. 3**) primarily are attributable to fractures and solution openings (Lines and Glass, 1975; Cox, 1976; Mills, 1989;

Mills and Huntoon, 1989). Spring-discharge measurements inventoried in the Bighorn aquifer in the Snake/Salt River Basin are summarized on **plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Bighorn aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Bighorn 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–2** and **E–5**).

Northern Ranges
The chemical composition of the Bighorn aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs and one well. Individual constituents are listed in **appendix E–2**. Major ion composition in relation to TDS for springs issuing from the Bighorn aquifer in the NR is shown on a trilinear diagram (**appendix F–2, diagram H**). TDS concentrations indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram H**). The TDS concentrations for the springs ranged from 37.1 to 107 mg/L, with a median of 96.0 mg/L. The TDS concentration for the well was 270 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Bighorn aquifer in the NR was suitable for most uses. No characteristics or constituents in the spring or well samples approached or exceeded applicable USEPA standards or State of Wyoming domestic or livestock water-quality standards. One characteristic in the well sample approached or exceeded applicable State of Wyoming standards for agricultural-use standards: SAR (exceeded WDEQ Class II standard of 8).

Overthrust Belt
The chemical composition of groundwater in the Bighorn aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from as many as eight springs. Summary statistics calculated for available constituents are listed in **appendix E–5**. Major ion composition in relation to TDS for springs issuing from the Bighorn aquifer in the OTB is shown on a trilinear diagram (**appendix F–5, diagram M**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5; appendix F–5, diagram M**). The TDS concentrations for the springs ranged from 104 to 188 mg/L, with a median of 160 mg/L. On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Bighorn aquifer in the OTB 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.

7.4.10 Gallatin aquifer

The physical and chemical characteristics of the Gallatin aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Gallatin aquifer is composed of saturated and permeable parts of the Upper Cambrian Gallatin Group or Limestone (**pls. 4, 5,** and **6**). The Gallatin Group or Limestone consists of interbedded, gray, mottled yellow and tan, thin-bedded to massive limestone and dolostone (dolomite); some green shale is present in the middle of the formation and some conglomerate is present in the lower part of the formation (Lines and Glass 1975; Oriel and Platt, 1980; Rubey and others, 1980; Love and others, 1992). In the Yellowstone Volcanic Area and Teton and Gros Ventre Ranges, the "Gallatin" is elevated to group rank and is composed of an upper formation, the Snowy Range Formation, and a lower formation, the Pilgrim Limestone (**pls. 5** and **6**).

Thickness of the Gallatin Limestone varies by geographic area in the Snake/Salt River Basin. Thickness of the Gallatin Group or Limestone in

the Gros Ventre Range ranges from about 180 to 250 ft (Love and Love, 1978; Love and others, 1992; Love and Love, 2000; Love, 2001a,b; Love and Reed, 2001a). Thickness of the Gallatin Group or Limestone in the Teton Range ranges from about 125 to 250 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972; Oriel and Moore, 1985; Love and others, 1992; Love and Reed, 2000, 2001b; Love, 2003a). Thickness of the Gallatin Group or Limestone in the Overthrust Belt ranges from about 120 to 250 ft (Pampeyan and others, 1967; Schroeder, 1969, 1972; Jobin, 1972; Albee and Cullins, 1975; Oriel and Platt, 1980; Oriel and Moore, 1985; Lageson, 1986; Love and others, 1992).

The Gallatin Group or Limestone is classified as an aquifer or confining unit by previous investigators (**pls. 4, 5,** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Gallatin Group or Limestone was probably a poor aquifer in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a minor aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). The investigators also considered the Gallatin aquifer to be part of a larger regional Paleozoic aquifer system composed of many different Paleozoic hydrogeologic units (**pls. 4** and **5**). In the eastern Gros Ventre Range and the Salt River Range, the Gallatin Group or Limestone is classified as an aquifer and is considered part of an aquifer system composed of other Paleozoic hydrogeologic units with varying amounts of hydraulic connection (**pls. 4** and **5**). In the Wyoming Water Framework Plan, the Gallatin Group or Limestone was classified as a minor aquifer throughout Wyoming (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Gallatin Group or Limestone in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer or confining unit (Ahern and others, 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein). In the upper Colorado River Basin and adjacent areas (including Green River Basin and parts of the Overthrust Belt), Geldon (2003) classified the Gallatin Group or Limestone as a regional confining unit (see Bartos and Hallberg, 2010, Figure 5-4). In the Wind River and Bighorn Basins east of the Snake/Salt River Basin, the Gallatin Group or Limestone was classified as a confining unit (**pl. 6**) (Bartos and others, 2012, and references therein).

Permeability of the dolomite that comprises much of the Gallatin aquifer is both primary (intercrystalline) and secondary (fractures and solution openings) (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Cox (1976, Sheet 1) speculated that the formation might yield a few tens of gallons per minute to wells. Large spring discharges (100 gal/min or more) inventoried as part of this study (**pl. 3**) primarily are attributable to fractures and solution openings (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Hydrogeologic information describing the Gallatin aquifer in the Snake/Salt River Basin, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Gallatin aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Gallatin 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–2, E–3,** and **E–5**).

Northern Ranges

The chemical composition of the Gallatin aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as two springs. Individual constituents are listed in **appendix E–2**. The TDS concentrations (75.8 and 2,480 mg/L) indicated that waters from the springs ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to slightly saline (1,000 to 2,999 mg/L) (**appendix E–2**).

Concentrations of some properties and constituents

in water from the Gallatin aquifer in the NR approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use and State of Wyoming standards for agricultural use: TDS (exceeded SMCL limit of 500 mg/L and WDEQ Class II standard of 2,000 mg/L) and sulfate (exceeded SMCL of 250 mg/L and WDEQ Class II standard of 200 mg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Jackson Hole
The chemical composition of the Gallatin aquifer in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituents are listed in **appendix E–3**. The TDS concentration (355 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for in the one sample, the quality of water from the Gallatin aquifer in JH 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.

Overthrust Belt
The chemical composition of groundwater in the Gallatin aquifer in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–5**. The TDS concentration (203 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for in the spring sample, the quality of water from the Gallatin aquifer in the OTB 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.

7.4.11 Park Shale, Meagher Limestone, and Wolsey Shale

Within the Snake/Salt River Basin, the Middle and Upper Cambrian Park Shale, Middle Cambrian Meagher Limestone, and Middle Cambrian Wolsey Shale are present only in the Yellowstone Volcanic area (**pl. 1; pl. 6**). The Park Shale and Wolsey Shale consist of green micaceous shale (Love and Christiansen, 1985, Sheet 2). The Meagher Limestone consists of blue-gray and yellow mottled hard limestone (Love and Christiansen, 1985, Sheet 2). Cox (1976, Sheet 1) speculated that wells completed in the formations probably would not yield more than a few gallons per minute. No data were located describing the physical and chemical hydrogeologic characteristics of the lithostratigraphic units in the Snake/Salt River Basin.

7.4.12 Gros Ventre aquifer and confining unit

The physical and chemical characteristics of the Gros Ventre aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Middle and Upper Cambrian Gros Ventre Formation (**pls. 4, 5,** and **6**) in the Overthrust Belt is composed of gray and tan, oolitic in part, limestone with green-gray micaceous shale in the middle of the formation (Lines and Glass, 1975; Oriel and Platt, 1980). Thickness of the Gros Ventre Formation in the Overthrust Belt ranges from about 400 to 1,300 ft (Schroeder, 1974, 1981; Lines and Glass, 1975; Oriel and Platt, 1980; Lageson, 1986).

In the Gros Ventre Range, the Gros Ventre Formation includes three members—the Park Shale, Death Canyon Limestone, and Wolsey Shale Members (Love and others, 1992; see Plate 5 under Mills, 1989; Mills and Huntoon, 1989). The Park Shale Member consists of olive-green, soft, flaky, micaceous shale with thin beds of flat-pebble limestone conglomerate; the basal part of

the unit has numerous large and small algal heads. Thickness of the Park Shale Member ranges from 150 to 350 ft. The Death Canyon Limestone Member consists of blue- to dark-gray, mottled brown and tan, dense, thin-bedded, cliff-forming limestone. The middle part of the Death Canyon Limestone Member contains 30 ft of flaky green shale with abundant trilobites; locally, at the base, a distinctive bed of brown-weathering dolomite is present. Thickness of the Death Canyon Limestone Member ranges from 300 to 370 ft. The Wolsey Shale Member consists of green to gray-green, soft, highly fissile micaceous shale that is siltier near the base; the lower part of the unit is very glauconitic and interbedded with sandstone, and the glauconite weathers to a red hematite color. Thickness of the Wolsey Shale Member ranges from 100 to 130 ft. The contact between the Wolsey Shale Member and the underlying Flathead Sandstone is transitional.

The Gros Ventre Formation is classified as an aquifer or confining unit by previous investigators (**pls. 4, 5,** and **6**). The Wyoming Water Planning Program (1972, Table III-2) speculated that the Gros Ventre Formation was a probable poor aquifer in the Snake/Salt River Basin (**pls. 4, 5,** and **6**). In the Salt River Range, the Gros Ventre Formation was classified as a confining unit (**pl. 4**) (Blanchard, 1990; Blanchard and others, 1990). In the eastern Gros Ventre Range, the formation was classified as both aquifer and confining unit—the Wolsey Shale and Park Shale Members composed primarily of shale were classified as confining units and the Death Canyon Limestone Member composed primarily of limestone was classified as an aquifer (**pl. 5**) (Mills, 1989; Mills and Huntoon, 1989). In the Wyoming Water Framework Plan, the Gros Ventre Formation was classified as a minor aquifer throughout Wyoming (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**).

Investigators for previous studies of the Gros Ventre Formation in areas adjacent to the Snake/Salt River basin have classified the formation as an aquifer or confining unit (Ahern and others, 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein) (**pls. 4** and **5**). Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as an aquitard (confining unit) in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). In the upper Colorado River Basin and adjacent areas (including Green River Basin, and parts of the Overthrust Belt), Geldon (2003) classified the Gros Ventre Formation as a regional confining unit (see Bartos and Hallberg, 2010, Figure 5-4). In the Wind River and Bighorn Basins east of the Snake/Salt River Basin, the Gros Ventre Formation was classified as a confining unit (**pl. 6**) (Bartos and others, 2012, and references therein). Because the unit consists of locally permeable zones interbedded with predominantly low-permeability lithologic units, the Gros Ventre Formation in the Snake/Salt River Basin was classified herein as a sequence of rocks that functions as both aquifer and confining unit, reflecting hydrogeologic characteristics that differ by location examined and the scale of the study.

Much of the Gros Ventre Formation consists primarily of poorly permeable rock. Permeability of the Gros Ventre Formation is attributable primarily to development of secondary permeability in the form of fractures and solution openings in limestone that composes parts of the unit (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Cox (1976, Sheet 1) speculated that the formation might yield a few tens of gallons per minute to wells. Shale within the formation has very little permeability, and the lithologic units act as confining units (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Large spring discharges (100 gal/min or more) inventoried as part of this study (**pl. 3**) are attributable to fractures and solution openings in limestone (Lines and Glass, 1975; Cox, 1976; Mills, 1989; Mills and Huntoon, 1989). Few hydrogeologic data are available describing the Gros Ventre aquifer and confining unit in the Snake/Salt River Basin, but spring-discharge measurements are summarized on **plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Gros Ventre aquifer and confining unit in the Snake/Salt River Basin are described in this section of the report. Groundwater quality of the Gros

Ventre 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–2** and **E–3**).

Northern Ranges
The chemical composition of the Gros Ventre aquifer and confining unit in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water sample from as many as five springs. Summary statistics calculated for available constituents are listed in **appendix E–2**. Major ion composition in relation to TDS for springs issuing from the Gros Ventre aquifer and confining unit in the NR is shown on a trilinear diagram (**appendix F–2, diagram I**). TDS concentrations indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2; appendix F–2, diagram I**). The TDS concentrations for the springs ranged from 86.8 to 148 mg/L, with a median of 107 mg/L. On the basis of the characteristics and constituents analyzed for, the quality of water from the Gros Ventre aquifer and confining unit in the NR 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.

Jackson Hole
The chemical composition of the Gros Ventre aquifer and confining unit in Jackson Hole (JH) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituents are listed in **appendix E–3**. The TDS concentration (308 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**appendix E–3**). On the basis of the characteristics and constituents analyzed for in the one sample, the quality of water from the Gros Ventre aquifer and confining unit in JH 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.

Overthrust Belt
The chemical composition of groundwater in the Gros Ventre aquifer and confining unit in the Overthrust Belt (OTB) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituents are listed in **appendix E–5**. The TDS concentrations (102 and 152 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–5**). On the basis of the characteristics and constituents analyzed for in the spring samples, the quality of water from the Gros Ventre aquifer and confining unit in OTB 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.

7.4.13 Flathead aquifer

The physical and chemical characteristics of the Flathead aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Flathead aquifer is composed of the Middle Cambrian Flathead Sandstone (**pls. 4, 5,** and **6**). The Flathead Sandstone consists of white to pink, tan, brown, fine-grained sandstone and some lenses of coarse-grained sandstone; the upper part includes some green, silty, micaceous shale interbeds, and the lower part is locally conglomeratic (Lines and Glass, 1975; Love and others, 1992). Much of the sandstone is quartzitic. In the Gros Ventre Range, thickness of the Flathead Sandstone ranges from 200 to 300 ft (Schroeder, 1969, 1972, 1976; Love and Love, 1978; Love and others, 1992; Love and Love, 2000; Love, 2001b; Love and Reed, 2001a). Thickness of the Flathead Sandstone in the Teton Range ranges from 150 to 240 ft (Pampeyan and others, 1967; Schroeder, 1969; Christiansen and others, 1978; Oriel and Moore, 1985; Love and others, 1992; Love and Reed, 2000; Love, 2003a).

Little information is available describing the hydrogeologic characteristics of the Flathead

Sandstone in the Snake/Salt River. Cox (1976, Sheet 1) speculated that the formation might yield a few tens of gallons per minute to wells. Because the formation was composed primarily of sandstone, Lines and Glass (1975) speculated that the Flathead Sandstone was probably a potential source of water in the Overthrust Belt.

Much of what is known about the hydrogeologic characteristics of the Flathead Sandstone is from the Green River Basin to the east and adjacent areas and elsewhere in Wyoming. Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a minor aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). In the Wyoming Water Framework Plan, the Flathead Sandstone was classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Flathead Sandstone in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern and others, 1981; Taylor and others, 1986; Lindner-Lunsford and others, 1989; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Snake/Salt River was tentatively retained herein (**pls. 4, 5,** and **6**). Few hydrogeologic data are available describing the Flathead aquifer in the Snake/Salt River, but spring-discharge measurements are summarized on **plate 3**.

Reported descriptions of permeability of the Flathead Sandstone in Wyoming vary by investigator and the geographic area examined. In the Wind River Basin and Granite Mountains area east of the Snake/Salt River Basin, Richter (1981, Table IV-1) reported that porosity and permeability is intergranular, but that secondary permeability is present along bedding-plane partings and as fractures associated with folds and faults; the investigator classified the Flathead Sandstone as a "major aquifer" in the Wind River Basin and adjacent Granite Mountains area east of the Snake/Salt River Basin. Similarly, in the Bighorn Basin east of the Absaroka Range in the Snake/Salt River Basin, previous investigators (Cooley, 1984, 1986; Doremus, 1986; Jarvis, 1986; Spencer, 1986) also reported intergranular porosity and permeability but also noted secondary permeability development along bedding-plane partings and as fractures associated with folds; all of these investigators classified the Flathead Sandstone as an aquifer. In contrast, Boner and others (1976) and Weston Engineering, Inc. (2008) noted that the Flathead Sandstone in the southern Powder River Basin in northeastern Wyoming and in the northern flank of the Laramie Mountains in south-central Wyoming was well cemented and poorly sorted with little primary (intergranular) permeability. In addition, Weston Engineering, Inc. (2008, p. II-4) also noted that bedding-plane partings may provide some permeability, but that 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."

Chemical characteristics

The chemical composition of groundwater in the Flathead aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Flathead 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–2**).

Northern Ranges

The chemical composition of the Flathead aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as two hot springs (Granite Hot Springs, about 15 miles east-northeast of Hoback Junction). Individual constituents are listed in **appendix E–2**. The TDS concentrations (670 to 826 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2**).

Concentrations of some properties and constituents in water from hot springs issuing from the Flathead aquifer in the NR approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was

measured at concentrations greater than health-based standards (both samples exceeded the USEPA MCL of 4 mg/L). Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: TDS (both samples exceeded the SMCL of 500 mg/L) and fluoride (both samples exceeded the SMCL of 2 mg/L).

Concentrations of some characteristics and constituents in water from hot springs issuing from the Flathead aquifer approached or exceeded State of Wyoming standards for agricultural and livestock use in the NR. One characteristic and one constituent were measured in environmental water samples from hot springs at concentrations greater than agricultural-use standards: chloride (both samples exceeded the WDEQ Class II standard of 100 mg/L) and SAR (1 of 2 samples exceeded the WDEQ Class II standard of 8). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.5 Precambrian basal confining unit

The physical and chemical characteristics of the Flathead aquifer in the Snake/Salt River Basin are described in this section of the report.

Physical characteristics

The Flathead aquifer is composed of the Middle Cambrian Flathead Sandstone (**pls. 4, 5,** and **6**). The Flathead Sandstone consists of white to pink, tan, brown, fine-grained sandstone and some lenses of coarse-grained sandstone; the upper part includes some green, silty, micaceous shale interbeds, and the lower part is locally conglomeratic (Lines and Glass, 1975; Love and others, 1992). Much of the sandstone is quartzitic. In the Gros Ventre Range, thickness of the Flathead Sandstone ranges from 200 to 300 ft (Schroeder, 1969, 1972, 1976; Love and Love, 1978; Love and others, 1992; Love and Love, 2000; Love, 2001b; Love and Reed, 2001a). Thickness of the Flathead Sandstone in the Teton Range ranges from 150 to 240 ft (Pampeyan and others, 1967; Schroeder, 1969; Christiansen and others, 1978; Oriel and Moore, 1985; Love and others, 1992; Love and Reed, 2000; Love, 2003a).

Little information is available describing the hydrogeologic characteristics of the Flathead Sandstone in the Snake/Salt River. Cox (1976, Sheet 1) speculated that the formation might yield a few tens of gallons per minute to wells. Because the formation was composed primarily of sandstone, Lines and Glass (1975) speculated that the Flathead Sandstone was probably a potential source of water in the Overthrust Belt.

Much of what is known about the hydrogeologic characteristics of the Flathead Sandstone is from the Green River Basin to the east and adjacent areas and elsewhere in Wyoming. Ahern and others (1981, Figure II-7, and Table IV-1) classified the formation as a minor aquifer in the Overthrust Belt and adjacent Green River Basin (**pls. 4** and **5**). In the Wyoming Water Framework Plan, the Flathead Sandstone was classified as a major aquifer (WWC Engineering and others, 2007, Figure 4-9) (**pls. 4, 5,** and **6**). Previous studies of the Flathead Sandstone in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern and others, 1981; Taylor and others, 1986; Lindner-Lunsford and others, 1989; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Snake/Salt River was tentatively retained herein (**pls. 4, 5,** and **6**). Few hydrogeologic data are available describing the Flathead aquifer in the Snake/Salt River, but spring-discharge measurements are summarized on **pl. 3**.

Reported descriptions of permeability of the Flathead Sandstone in Wyoming vary by investigator and the geographic area examined. In the Wind River Basin and Granite Mountains area east of the Snake/Salt River Basin, Richter (1981, Table IV-1) reported that porosity and permeability is intergranular, but that secondary permeability is present along bedding-plane partings and as fractures associated with folds and faults; the investigator classified the Flathead Sandstone as a "major aquifer" in the Wind River Basin and adjacent Granite Mountains area east of the Snake/

Salt River Basin. Similarly, in the Bighorn Basin east of the Absaroka Range in the Snake/Salt River Basin, previous investigators (Cooley, 1984, 1986; Doremus, 1986; Jarvis, 1986; Spencer, 1986) also reported intergranular porosity and permeability but also noted secondary permeability development along bedding-plane partings and as fractures associated with folds; all of these investigators classified the Flathead Sandstone as an aquifer. In contrast, Boner and others (1976) and Weston Engineering, Inc. (2008) noted that the Flathead Sandstone in the southern Powder River Basin in northeastern Wyoming and in the northern flank of the Laramie Mountains in south-central Wyoming was well cemented and poorly sorted with little primary (intergranular) permeability. In addition, Weston Engineering, Inc. (2008, p. II-4) also noted that bedding-plane partings may provide some permeability, but that 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."

Chemical characteristics

The chemical composition of groundwater in the Flathead aquifer in the Snake/Salt River Basin is described in this section of the report. Groundwater quality of the Flathead 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–2**).

Northern Ranges

The chemical composition of the Flathead aquifer in the Northern Ranges (NR) was characterized and the quality evaluated on the basis of environmental water samples from as many as two hot springs (Granite Hot Springs, about 15 miles east-northeast of Hoback Junction). Individual constituents are listed in **appendix E–2**. The TDS concentrations (670 to 826 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**appendix E–2**).

Concentrations of some properties and constituents in water from hot springs issuing from the Flathead aquifer in the NR approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured at concentrations greater than health-based standards (both samples exceeded the USEPA MCL of 4 mg/L). Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: TDS (both samples exceeded the SMCL of 500 mg/L) and fluoride (both samples exceeded the SMCL of 2 mg/L).

Concentrations of some characteristics and constituents in water from hot springs issuing from the Flathead aquifer approached or exceeded State of Wyoming standards for agricultural and livestock use in the NR. One characteristic and one constituent were measured in environmental water samples from hot springs at concentrations greater than agricultural-use standards: chloride (both samples exceeded the WDEQ Class II standard of 100 mg/L) and SAR (1 of 2 samples exceeded the WDEQ Class II standard of 8). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

Chapter 8

Groundwater Development and Basinwide Water Balance

Karl Taboga, Paul Taucher, and James Stafford

Several factors to consider when planning a groundwater development project include:

- 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 undermine the entire project.

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 a well, or a spring at its source. The consumptive use of a water resource, however, diminishes the amount of water available for other uses and effectively removes that water as a useable resource from 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 water is lost while the remainder is returned to the system. 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 in the form of return flows to surface waters or as recharge to groundwater. Other examples of partially consumptive uses (with the associated, consumptive constituent noted in parentheses) include livestock watering (animal growth and evaporation), reservoir storage (evapotranspiration), and domestic wastewater treatment including discharge from 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, 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 Snake/Salt River Basin using information compiled from multiple sources:

- Previous and current water plans for the Snake/Salt River Basin (Sunrise Engineering, 2003; WWDO, 2014);
- Numerous previous local and regional studies (**appendix B**, **chapter 7**);
- Groundwater permit data provided by the Wyoming State Engineer's Office (SEO) and the Idaho Department of Water Resources (IDWR); and
- SEO 2012 *Hydrographers' Annual Report Water Division 4* (SEO, 2013) available at: https://sites.google.com/a/wyo.gov/seo/documents-data/hydrographer-reports/division-iv-annual-reports.

8.1 Information from previous water plans

Total groundwater withdrawals, consumptive uses, and the methods used to quantify them in the Snake/Salt River Basin were described in the existing WWDC Statewide Framework Water Plan

(WWC Engineering and others, 2007), which compiled information from the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003), associated technical memoranda, and other on-line publications. Although the 2007 Statewide Water Plan summarized withdrawal and consumptive use information developed in the 2003 Snake/Salt 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. Estimates of consumptive uses associated with the 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 and basin-wide water balance

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 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 - 3 of **table 8-1a**.

The water resources of any river basin are not composed of static volumes of standing water. Unlike an area's mineral reserves, water is a dynamic resource that enters a basin in the form of precipitation or as surface and groundwater flows from adjacent areas. Likewise, water exits a river basin as effluent surface and groundwater flows or as water vapor resulting from evaporation, and transpiration from plants (see definition, **chapter 5**). It is important to understand the transient nature of water resources. For this reason, the Wyoming State Geological Survey (WSGS) generated a basin-wide water balance (**tables 8-2a** and **8-2b**) to provide an understanding of the magnitude, origin, and fate of water resources in the Snake/Salt River Basin.

8.2.1 Groundwater withdrawal and consumptive use estimations

Tables 8-1a through **8-1e** summarize and compare various groundwater withdrawal and consumptive use estimates from the SEO and previous WWDC water plans and technical memoranda (WWC Engineering and others, 2007; Sunrise Engineering, 2003; WWDO, 2014) for principal SEO listed water right uses. Some consumptive use estimates were obtained from *Technical Memorandum V, Future Water Use Projections* (BBC Research and Consulting, 2002) of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003). For this study, WSGS prorated 2002 annual consumptive use levels to those projected for 2032 from Technical Memorandum V to estimate uses in the basin for 2013. Consumptive use estimates from the median economic growth - normal water-demand year scenario were used for each "economic sector" (Agricultural, Municipal/ Rural Domestic Water Systems, Industrial and Recreational). These economic sectors combine the principal SEO-listed water right uses and, in addition, quantify consumptive uses resulting from recreational activities:

- Irrigation and stock watering are combined as agricultural uses (**table 8–1a**);
- Industrial uses (**table 8–1b**);
- Municipal supply and rural domestic are combined as municipal/water systems (**table 8–1c**);
- In the Snake/Salt River Basin, recreational uses (**table 8-1d**) consist primarily of snow-making at the area's ski resorts and golf course irrigation. Recreational uses, listed by the SEO under "Miscellaneous Uses" (SEO, 2014), are of significant

Table 8-1a. Groundwater withdrawal and consumptive use estimates for agricultural use wells (irrigation and stock watering) in the Wyoming portion of the Snake/Salt River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method/ Data sources/ Notes
[a] SEO permitted irrigation wells	30,869	no estimate		SEO permitted yields for irrigation wells through 02/27/12. (See Table 8-6)
	11,760	no estimate		SEO permitted yields for likely existing irrigation wells through 02/27/12. (See Table 8-6)
[a] SEO permitted livestock wells	5,794	no estimate		Total permitted yield through 02/27/12. (See Table 8-6)
	4,786	no estimate		Permitted yield for likely existing stock wells through 02/27/12. (See Table 8-6)
[b] Agricultural uses	no estimate	700	no estimate	Irrigation and livestock use estimates are aggregated as agricultural uses. Consumptive use estimate is pro-rated from 2002 and projected 2032 estimates in 2003 Snake/Salt River Basin Water Plan; normal demand mid growth scenario.

[a] Wyoming State Engineer's Office, 2012
[b] Sunrise Engineering, 2003

Table 8-1b. Groundwater withdrawal and consumptive use estimates for industrial use wells in the Wyoming portion of the Snake/Salt River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method / Notes
[a] Permitted industrial wells	1,312	no estimate		Total permitted yield through 02/27/12. (See Table 8-6)
	792	no estimate		Total permitted yield for likely existing wells through 02/27/12. (See Table 8-6)
[b,c] Industrial uses	50	50	-----	Consumptive use estimate is pro-rated from 2002 and projected 2032 estimates in 2003 Snake/Salt River Basin Water Plan; normal demand mid growth scenario.
	0	0		Estimated industrial water use for 2012 made by WWDO for the Snake/Salt River Basin Water Plan.
[d] WOGCC Conventional Oil & Gas produced water (2005-2011)	0	0	-----	WOGCC records show that all oil and gas wells in the Snake/Salt River Basin are plugged and abandoned and that there has been no production for the last three decades.

[a] Wyoming State Engineer's Office, 2012
[b] Sunrise Engineering, 2003
[c] Wyoming Water Development Office, 2014
[d] Wyoming Oil and Gas Conservation Commission, 2013

Table 8-1c. Groundwater withdrawal and consumptive use estimates for municipal and domestic use wells in the Wyoming portion of the Snake/Salt River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method / Notes
[a] Permitted municipal and domestic wells	130,591	no estimate		Total permitted yield through 02/27/12. (Table 8-6)
	110,187	no estimate		Permitted yield for likely existing wells through 02/27/12. (Table 8-6)
[b] Public Water Supplies/Rural domestic	14,100	8,400	60%	Aggregated domestic and municipal use (incl. associated commercial and subdivision uses); Withdrawal/consumptive use estimate pro-rated from 2002 and projected 2032 estimates in 2003 Snake/Salt River Basin Water Plan; normal demand mid growth scenario.
[c] Public Water Supplies/Rural domestic	No estimate	8,865	No estimate	Estimated combined municipal and rural domestic water use for 2012 made by WWDO for the Snake/Salt River Basin Water Plan

[a] Wyoming State Engineer's Office, 2012
[b] Sunrise Engineering, 2003
[c] WWDO, 2014

Table 8-1d. Groundwater withdrawal and consumptive use estimates for recreation in the Wyoming portion of the Snake/Salt River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method / Notes
[b] Recreational Uses	no estimate	150	no estimate	Recreational uses assumed to consist primarily of golf course irrigation and snow making at basin ski resorts. Consumptive use estimate pro-rated from 2002 and projected 2032 estimates in 2003 Snake/Salt River Basin Water Plan; normal demand mid growth scenario.

[a] Wyoming State Engineer's Office, 2012
[b] Sunrise Engineering, 2003

magnitude to include in this report; and

- Other diverse uses (**table 8–1e**) that involve miscellaneous, monitoring, testing, and multi-use wells are hereinafter referred to as minor uses.

Additionally, consumptive use estimates are provided from the 2012 Snake/Salt River Basin Plan Update (WWDO, 2014) for comparison to the values prorated from Technical Memorandum V of the 2003 Snake/Salt River Basin Plan (Sunrise Engineering, 2003). In cases where consumptive use estimates differ, the higher value is used in summary tables, such as **table 8-1f**. Finally, although the values developed for **tables 8-1a** through **8-1f** and **tables 8-2a** through **8-2d** are shown in some cases to a precision of one ac-ft., they are generally rounded to the nearest 50 ac-ft. in the following discussions. Percentages are typically carried to one decimal place in the tables; in some cases small percentages were carried to two decimal places (**table 8-2c**).

Estimates of total withdrawal and consumptive use volumes for the five economic sectors listed above are shown in **tables 8-1a** through **8-1e** and are aggregated in **table 8-1f**. Irrigation and stock watering uses are combined as agricultural uses in **table 8-1a**, and public supply and rural domestic uses are combined in **table 8-1c**. Total annual groundwater withdrawal is estimated at 14,600 ac-ft and the highest estimated value for annual consumptive use is 9,700 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 8-1f** because only SEO permitted withdrawal data (**table 8-1e**) is available and they were not addressed in previous water plans.

For other uses, potential volumes calculated from SEO allocated well yields are provided for comparison to consumptive use estimates obtained from previous technical memoranda. The large differences between SEO allocated well yields and actual use estimates show that the volumes of groundwater actually used constitute, in most cases, a minor 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" (11,760 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 that may be readily compared to estimates of actual consumptive uses. The estimates shown for agricultural withdrawals and consumptive uses of groundwater are aggregate values for both irrigation and stock watering (Sunrise Engineering, 2003). Irrigation consumptive uses in that report were based primarily on actual crop specific consumptive uses specified in Pochop and others (1992) applied to crop distribution data obtained from the agricultural industry in the Snake/Salt River Basin. The methodologies employed are explained in appendices D, E, F, G and P of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003).

Table 8-1a estimates total groundwater withdrawals and consumptive uses for irrigation and stock watering (combined as agricultural uses) obtained from various sources. Values from Technical Memorandum V (BBC Research and Consulting, 2002) of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) shown in **table 8-1a** are used in **table 8-1f**.

Table 8-1b estimates various classes of industrial groundwater withdrawals and consumptive uses compiled from SEO and WOGCC data and the 2012 Snake/Salt River Basin Water Plan (WWDO, 2014). The 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) identified three primary industrial water users: Star Valley Cheese Company, Northern Food, and Dairy and Water Star Bottling Company. Currently there is no significant industrial water use in the basin because operations have ceased at all three companies (WWDO, 2014). Historically, these industrial water demands were supplied from municipal groundwater sources in Thayne and Afton (BBC Research and Consulting, 2002).

WOGCC records indicate that there has been no production or injection of groundwater from oil

Table 8-1e. Permitted annual groundwater withdrawal rates for SEO monitor, multi-use and other wells in the Wyoming portion of the Snake/Salt River Basin.

SEO permitted use	[a]Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Estimation method / Notes (See Table 8-6)
Permitted monitor wells	0.0	no estimate	Total permitted yield through 02/27/12
	0.0	no estimate	Permitted yield for likely existing wells through 02/27/12
Permitted "other wells"	268,938	no estimate	Total permitted yield through 02/27/12
	121,792	no estimate	Permitted yield for likely existing wells through 02/27/12
Permitted "multi-use wells"	44,053	no estimate	Total permitted yield through 02/27/12
	27,693	no estimate	Permitted yield for likely existing wells through 02/27/12

[a] Wyoming State Engineer's Office (2012)

Table 8-1f. Total groundwater withdrawal and consumptive use estimates for all uses in the Snake/Salt River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual Consumptive-Use (ac-ft/yr)	Percent Consumptive Use	Estimation method / Notes
Total permitted yield Wyoming[a]	481,557	no estimate		Total permitted yield through 02/27/12 (See Table 8-6)
	277,010	no estimate		Permitted yield for likely existing wells through 02/27/12 (See Table 8-6)
Total permitted yield Wyoming, Idaho	[a,b] 499,640	no estimate		6,161 WSEO permits as of 02/27/12 89 IDWR permits as of 09/20/12 (See Tables 8-6, 8-7, 8-8)
Estimated withdrawals and consumptive uses of groundwater in Wyoming for agricultural, industrial, public and rural domestic water supplies and recreation.	14,600	8,600	58.9%	Pro-rated from 2002 and projected 2032 estimates in 2003 Snake/Salt River Basin Water Plan [c] normal demand/mid growth scenario Technical Memorandum V, Exhibits 6 and 7.
	No estimate	9,761	N/A	Estimated total groundwater use for 2012 made by WWDO for the Snake/Salt River Basin Water Plan
	No estimate	9,700	N/A	Totals of high use estimates from Tables 8-1a, 8-1b, 8-1c and 8-1d.

[a] Wyoming State Engineer's Office (2012)
[b] Idaho Department of Water Resources (2012)
[c] Sunrise Engineering (2003)
[d] WWDO, 2014

and gas operations in the Snake/Salt River Basin during the 2002 -2013 period of record.

Table 8-1c estimates combined municipal and domestic groundwater withdrawals and consumptive uses . The ranges of consumptive uses, shown and aggregated with other uses in **table 8-1f**, are compiled from Technical Memorandum V (BBC Research and Consulting, 2002) of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) and from the 2012 Snake/Salt River Basin Water Plan (WWDO, 2014). All municipal and rural domestic water demands are supplied by groundwater (BBC Research and Consulting, 2002; WWDO, 2014).

Table 8-1d shows recreational consumptive uses of groundwater from Technical Memorandum V (BBC Research and Consulting, 2002) of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003)**.**

Table 8-1e contains SEO permitted withdrawal information for several "minor uses" - monitoring, other, and multi-use wells.

Table 8-1f: Total groundwater withdrawal and consumptive use estimates are shown for principal listed uses from the SEO and the Idaho Department of Water Resources (IDWR). Values obtained from **tables 8-1a** through **8-1d** were compiled from Technical Memorandum V (BBC Research and Consulting, 2002) of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003).

8.3 Basinwide water balance

Tables 8-2a and **8-2b** contain mass balance, water budget calculations for the Wyoming portion of the Snake/Salt River Basin. The primary objective of the water balance analysis is to provide an estimate of basinwide evapotranspiration. In the process, withdrawal, consumptive use, and recharge data from this and other chapters in this report are conveniently compiled into one table (**table 8.2**). Armed with these estimates, first order approximations can be made of the proportions of precipitation destined for recharge, evapotranspiration, surface water outflows, and consumptive uses from water resource development.

The analysis contained in **table 8-2a** was adapted from the general water budget equation (Fetter, 2001):
Evapotranspiration = (precipitation + surface inflow + imported water + groundwater inflow) – (surface water outflow + groundwater outflow + reservoir evaporation + exported water + recharge) ± changes in surface water storage ± changes in groundwater storage

The assumptions used in this water balance are:

- Water is neither imported nor exported into or from the Snake/Salt River Basin.
- Basin groundwater inflows and outflows equal zero.
- Groundwater and surface water depletions are limited to consumptive uses from the municipal/domestic, livestock, and industrial sectors (i.e., SEO permitted uses).
- The water budget mass balance model examines annual fluxes of water resources in the Snake River Basin. Therefore, it is assumed that long term changes in stored surface and groundwater equal zero.

8.3.1 Precipitation

Precipitation is the ultimate source of groundwater recharge. Average annual precipitation volume in the Snake/Salt River Basin for the 30-year period of record (POR) from 1981 to 2010 was calculated using GIS software and PRISM data (http://prism.oregonstate.edu/ - **fig**. **3-3**) at 9,137,300 ac-ft.

8.3.2 Surface water inflows and outflows

Average annual stream inflow and outflow data for the Wyoming portion of the basin were obtained from the USGS (http://water.usgs.gov/). Only USGS streamflow gaging station 13025500 on Crow Creek near Fairview, Wyoming monitors inflows from the small streams that enter Wyoming from tributaries in Idaho. Annual outflow data

Table 8-2a. Snake/Salt River Basin water resources mass balance.

WATER BALANCE PARAMETERS[a]		Average Annual Volume (ac-ft)
Precipitation (1981 - 2010 - Figure 3-3)[b]		9,137,300
Total surface water inflows[c]	+	43,700
Total surface water outflows[c]	-	4,643,100
Evaporation from reservoirs[d]:	-	72,200
Surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses[d]	-	9,800
Total estimated Snake/Salt River Basin recharge (Table 6-3)	-	1,706,300
Basin-wide evapotranspiration	=	2,749,600

Comparative estimates

Estimated evapotranspiration in the Snake/Salt River Basin from the USGS climate and land-cover data regression[e] .

Total evapotranspiration 4,150,900 acre-feet

[a] Fetter , C. W., 2001
[b] PRISM Climate Group, 2012
[c] USGS, 2014
[d] Wyoming Water Development Office, 2014
[e] Sanford and Selnick, 2013

Table 8-2b. Estimated recharge and total evapotranspiration levels in the Wyoming portion of the Snake/Salt River Basin.

WATER BALANCE PARAMETERS[a]	% of Precipitation [b]
Net stream outflows[c]	50.10%
Evaporation from reservoirs[d]:	0.80%
Surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses[d]	0.10%
Total estimated Snake/Salt River Basin recharge (Table 6-3)	19.00%
Basin-wide evapotranspiration	30.00%
Total	100.00%

[a] Fetter , C. W., 2001
[b] PRISM Climate Group, 2012
[c] USGS, 2014
[d] Wyoming Water Development Office, 2014

were recovered from USGS stream gaging stations 13022500, 13023000, 13046995, and 13027500. These stations are all sited on effluent reaches of the Snake, Salt, Falls, and Greys rivers near Wyoming's border with Idaho.

8.3.3 Evaporation from reservoirs

Evaporation data from the basin's reservoirs were obtained from Technical Memorandum XII of the 2012 Snake/Salt River Basin Water Plan (WWDO, 2014).

8.3.4 Depletions from municipal/ domestic, livestock, and industrial uses)

Surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses were obtained from the 2012 Snake/Salt River Basin Water Plan (WWDO, 2014). Agricultural uses were not considered since 99.9 percent of irrigation water is lost to evapotranspiration, and return flows that recharge underlying aquifers or discharge to surface water bodies (Colorado State University, 2013).

8.3.5 Total estimated Snake/Salt River Basin recharge

The recharge value shown is the "best total recharge" estimate for sedimentary aquifers calculated on **tables 6-2** and **6-3** from the recharge fraction data in Hamerlinck and Arneson (1998) and PRISM (2013) precipitation data for the 1981 – 2010 period of record (POR).

8.3.6 Estimated basin-wide evapotranspiration

The water balance model adapted from Fetter (2001) and presented in **table 8-2a** places basin-wide evapotranspiration at 2,749,600 ac –ft per year. For comparison, a second estimate of actual evapotranspiration (4,150,900 ac-ft per year) in the Snake/Salt River Basin is shown at the bottom of **table 8-2a**. This estimate was obtained using a GIS based regression model developed by the USGS (Sanford and Selnick, 2013) from climate and land-cover data. The calculated results of the two methods in the Snake/Salt River Basin do not produce the close agreement previously seen in identical analyses conducted for the more arid Bear (Taboga and others, 2014) and Platte River basins (Taucher and others, 2013). The large discrepancy between the two estimates (1,401,300 ac-ft, or 51 percent) suggests that a significant portion of recharge in the semi-humid Snake/Salt River may return to streamflows in the form of baseflow. This premise is further supported by the potentiometric surface shown in **figure 7-3** that indicates that groundwater flows from Quaternary units to the Snake River.

8.4 Magnitude, origin, and fate of water resources in the Snake/Salt River Basin

Table 8-2b shows that approximately 30 percent of precipitation is lost to evapotranspiration in the Snake/Salt River Basin, about 19 percent recharges the basin's aquifers, and nearly 50 percent leaves as stream outflow. Evaporation from reservoirs constitutes about 0.8 percent of total basin precipitation. Combined surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses comprise 0.1 percent of precipitation.

Table 8-2c summarizes various average groundwater consumptive use estimates from **tables 8-1a** through **8-1d** as percentages of estimated recharge. Aggregated municipal and domestic consumptive uses constitute about 0.5 percent of recharge. Estimated total annual consumptive uses (9,700 ac-ft **- table 8-1e**) constitute about 0.6 percent of annual average recharge.

Estimated recharge (**table 8-2c**) far exceeds average annual withdrawals of groundwater. 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.

Table 8-2d evaluates future groundwater requirements relative to recharge. The 2012 Snake/Salt River Basin Water Plan (WWDO,

Table 8-2c. Summary of groundwater use statistics as percentage of recharge in the Wyoming portion of the Snake/Salt River Basin.

Groundwater-use statistics	Annual volume (acre-feet)	Percentage of calculated recharge
[1]Estimated recharge (acre-feet) to sedimentary aquifers	1,706,300	-----
[3]Average annual groundwater consumptive uses		
[2] Agricutural uses (irrigation and stock watering)	700	0.04%
[2]Municipal & domestic	8,850	0.52%
[2]Industrial	0	0.00%
[2]Recreational	150	0.01%
[2]TOTAL	9,700	0.57%

[1]Table 8-2b
[2]Tables 8-1a-d
[3]Table 8-1f

Table 8-2d. Summary of future groundwater requirements as percentages of recharge.

Economic scenario	***Low growth***	***Mid growth***	***High growth***
Groundwater demand - 2032 consumptive use (acre-feet)	9,363	10,832	13,071
Percentage of estimated recharge	0.5%	0.6%	0.8%

[a] WWDC, 2012

2014) provides use factor-based projections of total, combined, annual withdrawals and consumptive uses for agricultural, municipal/rural domestic, recreational, and industrial uses in 2032. The analysis examines normal and maximum water demand for low, moderate, and high economic growth scenarios. Projected future annual groundwater requirements for the 20-year timeframe are determined as percentages of annual recharge estimated in **chapter 6**.

Overall, groundwater consumptive uses projected for 2032 range from 0.5 percent of recharge for the low growth to 0.8 percent for the high growth scenario. Estimated recharge volumes are likely adequate to meet not only current withdrawals (**table 8-2c**) but future groundwater demands, as well. The potential for overutilization 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 Snake/Salt 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 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) and the 2007 Statewide Framework Water Plan (WWC Engineering and others, 2007). **Tables 8-6** through **8-8** show the number of groundwater permits by use for the portions of Wyoming and

Idaho, respectively. The "other" category includes miscellaneous wells.

8.4.1 Agricultural uses (aggregated irrigation, livestock watering, and dairy)

Irrigation, livestock watering, and dairy uses were aggregated as agricultural uses in the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering and others, 2003). Direct measurements of groundwater volumes used for irrigation are not presented in the 2003 Snake/Salt River Basin report (Sunrise Engineering, 2003), in the 2007 State Framework Water Plan (WWC Engineering and others, 2007), or in the 2012 Snake/Salt River Basin report (WWDO, 2014). Instead, irrigation consumptive uses were calculated on actual crop-specific consumptive uses delimited/defined in Pochop and others (1992) and applied to crop distribution data obtained from the agricultural industry in the Snake/Salt River Basin. From these, total diversions and consumptive uses were generated for six cases formulated for low, moderate, and high economic growth scenarios within the context of both normal and maximum water demand conditions determined for the year 2002 (Sunrise Engineering, 2003). The same procedure was used to predict total irrigation diversions and consumptive uses for the year 2032. The Sunrise Engineering, (2003) study estimated the proportions of groundwater and surface water that constitute total withdrawals and consumptive use for all evaluated uses.

In the Snake/Salt River Basin, most irrigation wells are located along the river and its tributaries where water is obtained from relatively shallow alluvial deposits. Irrigation uses are largely consumptive due to evapotranspiration. Within the Snake/Salt River Basin, 57 SEO and one IDWR permits have been issued solely for irrigation use. Updated data for total permits and permitted yields from the SEO and IDWR are shown in **tables 8-6** and **8-7** and in **figure 8-1.**

Withdrawals and consumptive uses for livestock watering were calculated in the 2003 Water Plan (Sunrise Engineering, 2003) using stock-specific daily water requirements of 12 gal/day/animal for cattle and 2 gal/day/animal for sheep. It was assumed that all of the water used for livestock watering is consumptively used. In the Snake/Salt River Basin, 211 SEO permits and two IDWR permits have been issued solely for stock watering (**tables 8-6** and **8-7**).

8.4.2 Municipal/water systems (aggregated municipal/rural domestic water systems)

Municipal and rural domestic water systems were aggregated as municipal/water systems in the 2003 and 2012 Water Plans (Sunrise Engineering, 2003; WWDO, 2014). Municipal/rural water systems (http://www2.epa.gov/region8-waterops) supply water year-round to essentially the same population. Information for municipal water systems was obtained directly from water system operators and administrators in Afton, Alpine, Thayne, and Jackson. Average and peak use volumes for unincorporated communities were calculated by multiplying per capita values obtained from the documented municipal systems (Afton, Alpine, Thayne, and Jackson) by the population served.

Municipal/water systems use constitutes the majority of overall groundwater consumptive uses in the Snake/Salt River Basin (**table 8-2c**). As of February 27, 2012, the SEO issued 21 permits for exclusive municipal use and 3,751 domestic use permits in the Snake/Salt River Basin (**table 8-6**). IDWR has issued 48 domestic use permits in the Snake/Salt River Basin (**table 8-7**). In addition to the municipal use permits, some of the wells that supply water to the basin's municipalities and communities (**tables 8-8** through **8-10**) are permitted as multiple use or miscellaneous wells.

8.4.3 Recreational and environmental uses

In the Snake/Salt River Basin recreational water consumptive use is associated with snow making at ski resorts and turf irrigation at golf courses. Only a few recreational uses, such as snowmaking and turf irrigation, are consumptive. Based on prorated

levels of use from the Snake/Salt River Basin 2003 Water Plan (Sunrise Engineering, 2003), it is estimated that about 150 ac-ft is used for the recreation sector, which is expected to grow of 50 percent by 2032 (**table 8-2c**).

8.4.4 Industrial uses

The 2003 Water Plan (Sunrise Engineering, 2003) identified only three industrial water users in the basin and determined that industrial water use was about 130 acre-feet/year. Currently, operations have ceased at all three businesses (WWDO, 2014), and there is negligible industrial water use (**table 8-1b**) in the Snake/Salt River Basin. Permitted yields for SEO industrial permits are provided on **table 8-1b** for the reader's information.

8.5 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 **chapter 7** discussion of hydrogeologic units in the Snake/Salt River Basin. **Chapter 7** summarizes the physical, hydrogeologic, and chemical characteristics of the principal hydrogeologic units in the Snake/Salt River Basin including the known dynamics of recharge, discharge, and groundwater circulation.

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 Snake/Salt River Basin. Many of these studies were used to compile the information presented in **chapter 7**.

8.6 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 and the Department of Water Resources (IDWR) in Idaho. For this study, the WSGS acquired groundwater permit data from both agencies. The SEO provided information for 6,161 groundwater permits through February 27, 2012, including 1,541 newer permits issued after December 31, 2003 (**table 8-6**). IDWR provided data for 89 Idaho groundwater permits through September 20, 2012. 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 online 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).

Information on specific groundwater permits from the IDWR can be accessed at: http://www.idwr.idaho.gov/WaterManagement/default.htm.

Permits to appropriate groundwater in the Snake/Salt 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 Snake/Salt River Basin. Groundwater permit data is tabulated in this section to summarize the number of permits by:

1. SEO permit status, depth range, and yield range;
2. Class of use (SEO, IDWR);
3. SEO municipal use, including producing hydrogeologic unit;
4. WDEQ Source Water Assessment Program (SWAP).

In addition, permit data are tabulated on maps depicting locations of likely drilled wells (**figs. 8-1** through **8-7**). SEO data are tabulated and mapped in this study for all permits through February 2012 and for permits from 2003 through February 2012 to illustrate development over the last decade.

8.6.1 Groundwater permits by permit status

Table 8-3 shows the number of groundwater permits issued by the SEO under five permit-status categories. **Table 8-3** does not include permits from the IDWR. In Wyoming, the status categories are:

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. *Undefined* – a permit without a designated status. These include the following discontinued status categories:
   - *Abandoned* – SEO has received a notice that the well has been physically abandoned.
   - *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).
   - *Cancelled* – the permit has been cancelled, generally by the original permit applicant.

The SEO issues permits granting water rights to applicants. This does not necessarily mean that a well has been completed and in most cases, it is not known with any certainty whether a well was installed in association with a specific permit. To estimate the number of wells that have likely been completed for each use, the WSGS assumed that wells probably have been completed for fully adjudicated, complete, abandoned and unadjudicated permits. In contrast, wells are likely not completed in association with incomplete and undefined permits. **Table 8-3** summarizes the number of likely drilled wells for each use in the Snake/Salt River Basin. Based on these assumptions, at least 96 percent of wells permitted through 2003 are likely to have been installed (i.e., completed) compared to at least 74 percent of wells permitted since 2003.

8.6.2 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 permits by yield range. **Tables 8-4** and **8-5** do not include permits from the IDWR.

Table 8-3. SEO groundwater permits in the Snake/Salt River Basin listed by permit status.

Permit Status	All Permits through 2003	New Permits since 2003
Fully Adjudicated	248	28
Complete	3,950	638
Unadjudicated	4	65
Incomplete	221	408
Undefined	197	402
Total Permits	4,620	1,541
Probable Wells Drilled	4,423 - 4,620 (96 - 100%)	1,139 - 1,541 (74 - 100%)

Approximately 99.9 percent of all SEO groundwater permits for which depth data are available are for wells less than 500 feet deep, and approximately 87 percent are for wells less than 100 feet deep. All but four SEO groundwater permits issued from 2003 through February 2012 were for wells less than 500 feet deep, and approximately 82 percent were for wells less than 100 feet deep. In the SEO database, many of the permits (53 percent issued after 2003 and 19 percent overall) do not include well depth. Of the 5,287 groundwater permits in the Snake/Salt River Basin database for which yield information is available, approximately 85 percent of all permits and 70 percent of wells permitted since 2003 are allowed yields of 0-25 percent. Less than two percent of permits issued both since 2003 and in total are for yields greater than 1,000 gpm. Approximately seven percent of all permits and thirteen percent of permits issued after 2003 allow yields greater than 100 gpm. Many of the permits (11 percent issued after 2003 and 14 percent overall) in the SEO database do not include permitted yield.

Permitted depths and yields, and the mapped permit locations on **figures 8-1** through **8-7** illustrate that most wells in the Snake/Salt River Basin are planned and completed in near-surface, Quaternary hydrogeologic units.

8.6.3 Groundwater permits by use: tables, figures, and matrix tables

Groundwater permit information, by use, is presented in **tables 8-6** and **8-7** and **figures 8-1** through **8-7**, and the matrix tables contained in the figures. This information was obtained from the SEO and the IDWR. Both of these agencies

Table 8-4. SEO groundwater permits in the Snake/Salt River Basin listed by depth range.

Depth Range(feet)	All Permits		Cumulative	
	Permits	Percentage	Permits	Percentage
1-50	3637	72.51%	3637	72.51%
51-100	725	14.45%	4362	86.96%
101-500	648	12.92%	5010	99.88%
501-1000	6	0.12%	5016	100.00%
> 1000	0	0.00%	5016	100.00%
Total Permits with Depth information	5016	--	--	--
Permits with no Depth information	1145	18.58%	6161	--
Total Permits	6161	(of Total)	--	--

Depth Range(feet)	New Permits since 2003		Cumulative	
	Permits	Percentage	Permits	Percentage
1-50	479	65.62%	479	65.62%
51-100	119	16.30%	598	81.92%
101-500	128	17.53%	726	99.45%
501-1000	4	0.55%	730	100.00%
> 1000	0	0.00%	730	100.00%
Total Permits with Depth information	730	--	--	--
Permits with no Depth information	811	52.63%	1541	--
Total Permits	1541	(of Total)	--	--

Table 8-5. SEO groundwater permits in the Snake/Salt River Basin listed by yield range.

	All Permits		Cumulative	
Yield Range(gpm)	Permits	Percentage	Permits	Percentage
1-25	4516	85.42%	4516	85.42%
26-100	412	7.79%	4928	93.21%
101-500	246	4.65%	5174	97.86%
501-1000	71	1.34%	5245	99.21%
> 1000	42	0.79%	5287	100.00%
Total Permits with Yield information	5287	--	--	--
Permits with no Yield information	874	14.19%	6161	--
Total Permits	6161	(of Total)	--	--

	New Permits since 2001		Cumulative	
Yield Range(gpm)	Permits	Percentage	Permits	Percentage
1-25	960	69.72%	960	69.72%
26-100	241	17.50%	1201	87.22%
101-500	127	9.22%	1328	96.44%
501-1000	27	1.96%	1355	98.40%
> 1000	22	1.60%	1377	100.00%
Total Permits with Yield information	1377	--	--	--
Permits with no Yield information	164	10.64%	1541	--
Total Permits	1541	(of Total)	--	--

Table 8-6. SEO groundwater permits in the Snake/Salt River Basin listed by intended use.

Well Type	WSEO Code	Total Number of Permits	New Since 2001	Total Permitted Yield (gpm)	Total Likely Yield* (gpm)
Municipal	MUN	21	5	12,900	8,800
Domestic	DOM	3,751	763	68,719	60,067
Industrial	IND	7	2	820	495
Irrigation	IRR	57	13	19,293	7,350
Stock	STK	211	53	3,621	2,991
Monitor	MON	677	72	0	0
Other	MIS, blank	905	482	168,086	76,120
Multi-Use	various	532	151	27,533	17,308
Total		6,161	1,541	300,972	173,131

**Includes only wells that are Fully Adjudicated, Complete, and Unadjudicated.*

Table 8-7. Idaho DWR groundwater permits in the Snake/Salt River Basin listed by intended use.

Well Type	Total Number of Permits	New Since 2003	Total Permitted Yield (gpm)
Municipal	0	0	0
Domestic	48	18	10,763
Industrial	1	0	0
Irrigation	1	0	300
Stock	2	2	0
Monitoring	30	17	179
Other	6	1	25
Multi-use	1	0	35
Total	89	38	11,302

issue permits granting water rights to applicants. In many cases, especially with older permits, it is not known with any certainty whether a well or spring improvement was actually installed in association with a specific permit. Furthermore, existing facilities might have been abandoned after some time and are no longer being used beneficially. Any examination of permitted uses must explain how the permit data was processed and what it actually represents. The permit data presented in the following two sections differs between the figures and the tables:

- **Tables 8-6** and **8-7** show the number of groundwater permits issued in Wyoming and Idaho, respectively, by permitted use regardless of permit status (**section 8.4.1**). This means that all permits issued are listed without evaluating if a well was installed. The tables list six single primary use categories (municipal, domestic, industrial, irrigation, stock, and monitoring), an "other" category for all other single uses, and a "multi-use" category for permits that list more than one use (approximately 8 percent of all groundwater permits in the Snake/Salt River Basin are for multiple uses). The "other" category includes permits issued for "miscellaneous uses" and for minor uses, such as test wells. The number of permits given for a single use (e.g., 21 total permits for municipal use in **table 8-6**) includes neither "multi-use" permits which may allow municipal use in addition to other uses nor those permits listed as "other" which may allow municipal withdrawals. Additionally, values for "total permitted yield" calculated by summation of all permits with listed yields and "total likely yield" determined by analysis of permit status are provided.

- **Figures 8-1** through **8-7** show the number of "likely drilled wells", determined by analysis of permit status (**section 8.4.1**) for each of the six primary use categories (municipal, domestic, industrial, irrigation, stock, and monitoring) and miscellaneous wells. This includes permits where one use is listed. For example, the number of municipal wells is determined by counting single use "municipal" wells and any "multi-use" permits which include "municipal" as one of the permitted uses. Thus, multi-use wells are counted several times, once for each listed use.

- Matrix tables contained in each of the figures, present the number of all permits issued for each use combined in both states (**fig. 3-1**) regardless of permit status. This includes permits where one use is listed, for example "municipal" as well as "multi-use" permits which include "municipal" as one of the permitted uses.

8.6.3.1 Groundwater permits by use: Tables 8-6 through 8-10

Tables 8-6 and **8-7** show that most groundwater permits in the Snake/Salt River Basin are for domestic use at individual residences, followed by wells categorized as "other" and designated for monitoring.

Additionally, total likely yields (permitted yields from wells that are likely to be completed) constitute a fraction of the total permitted yields. A comparison of total likely yields to total permitted yields for each use suggests that a higher proportion of domestic and stock wells were completed and used beneficially than other type of wells.

Tables 8-8 and **8-9** are expanded summary tables for SEO permits that include municipal uses, and **table 8-10** summarizes information on SWAP wells and springs that are used for both municipal and non-community public water supply. A brief discussion of the SWAP is provided in **section 8.4.3.7**. The SWAP provides some information beyond what is available in the SEO groundwater permits data.

8.6.3.2 Groundwater permit location maps and matrix tables, by use

Seven maps (**figs. 8-1** through **8-7**) were prepared for this study to illustrate the geospatial distribution of groundwater permits according to use in the Snake/Salt River Basin. Only permits for wells that were likely to have been drilled (including abandoned wells) are included on **figures 8-1** through **8-7.** Groundwater permits are mapped relative to their date of issue (before or after January 1, 2003) on Snake/Salt River Basin scale maps and by total well depths on subregion scale figures. Figures have been provided for the following permitted uses:

- Irrigation (**fig**. **8-1**)
- Livestock (**fig**. **8-2**)
- Municipal (**fig**. **8-3**)
- Domestic (**fig**. **8-4**)
- Monitoring (**fig**. **8-5**)
- Miscellaneous-use and other wells (**fig**. **8-6**)
- Industrial-use wells (**fig**. **8-7**)
- USGS spring locations are shown on **figure 7-2**

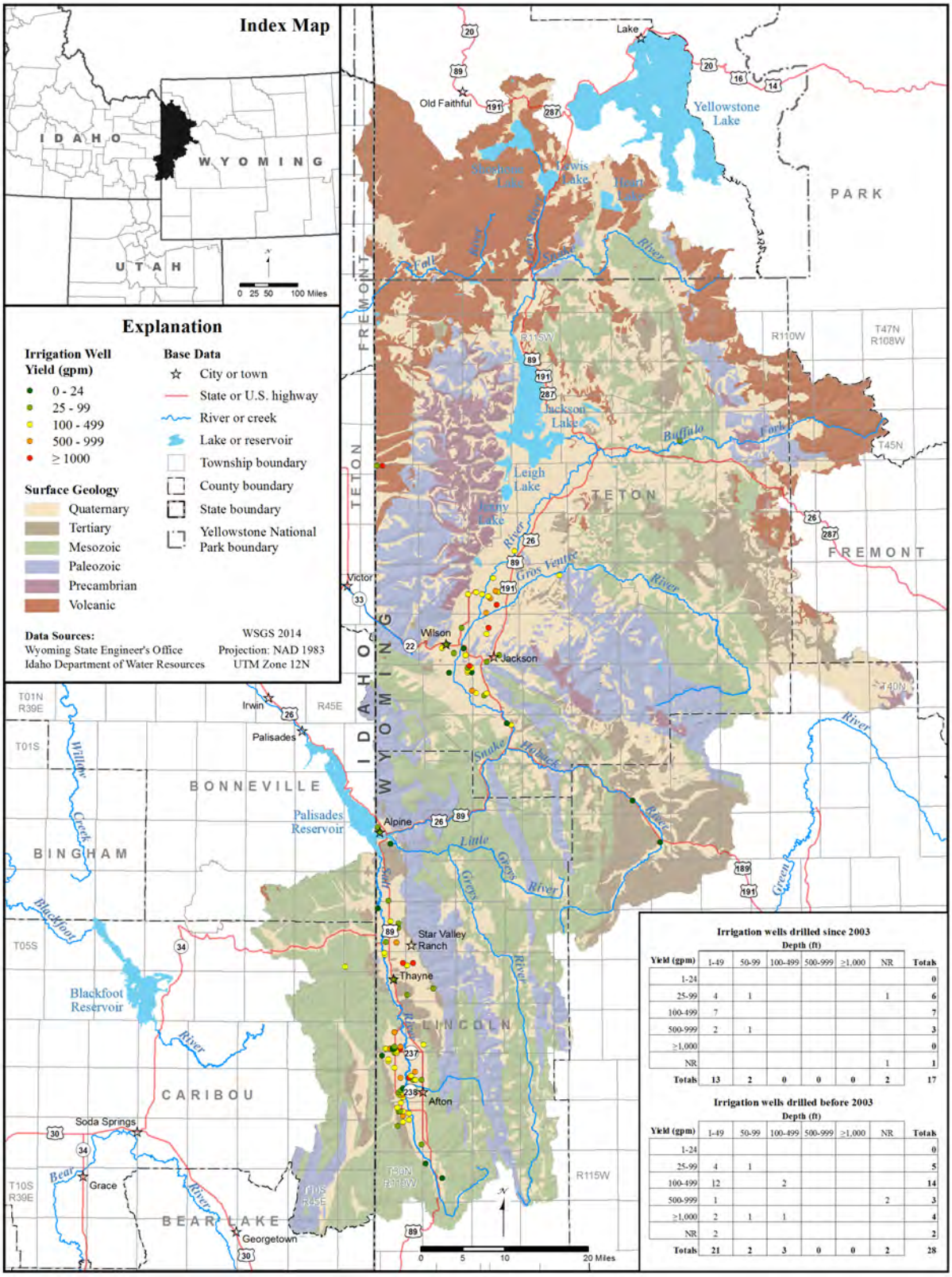
Figures 8-1 through **8-7** differentiate groundwater permits issued from January 1, 2003 through February 27, 2012 in order to evaluate how groundwater development in the Snake/Salt River Basin has proceeded during the past decade. Substantial groundwater development has occurred in the Snake/Salt River Basin since the 2003 Groundwater Determination (Sunrise Engineering, 2003). Consistent with the historic trend, it is clear that most permits issued over the 2003 - 2012 period of record in the Snake/Salt River Basin continue to target Quaternary and Tertiary hydrogeologic units.

Matrix tables that correlate ranges of well depths and yields for all permits issued 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 Snake/Salt 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 shown on **figures 8-1** through **8-7**, the number of permits on the insert matrix tables does not match the number of permits depicted on the maps.

Figure 5-10 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.

8.6.3.3 Irrigation use permits

Tables 8-6 and **8-7** list 58 groundwater permits for irrigation use (IRR) in the Snake/Salt River Basin, with 57 in Wyoming and one in Idaho. **Figure 8-1** shows the distribution of likely drilled irrigation wells in the entire Snake/Salt River Basin, issued



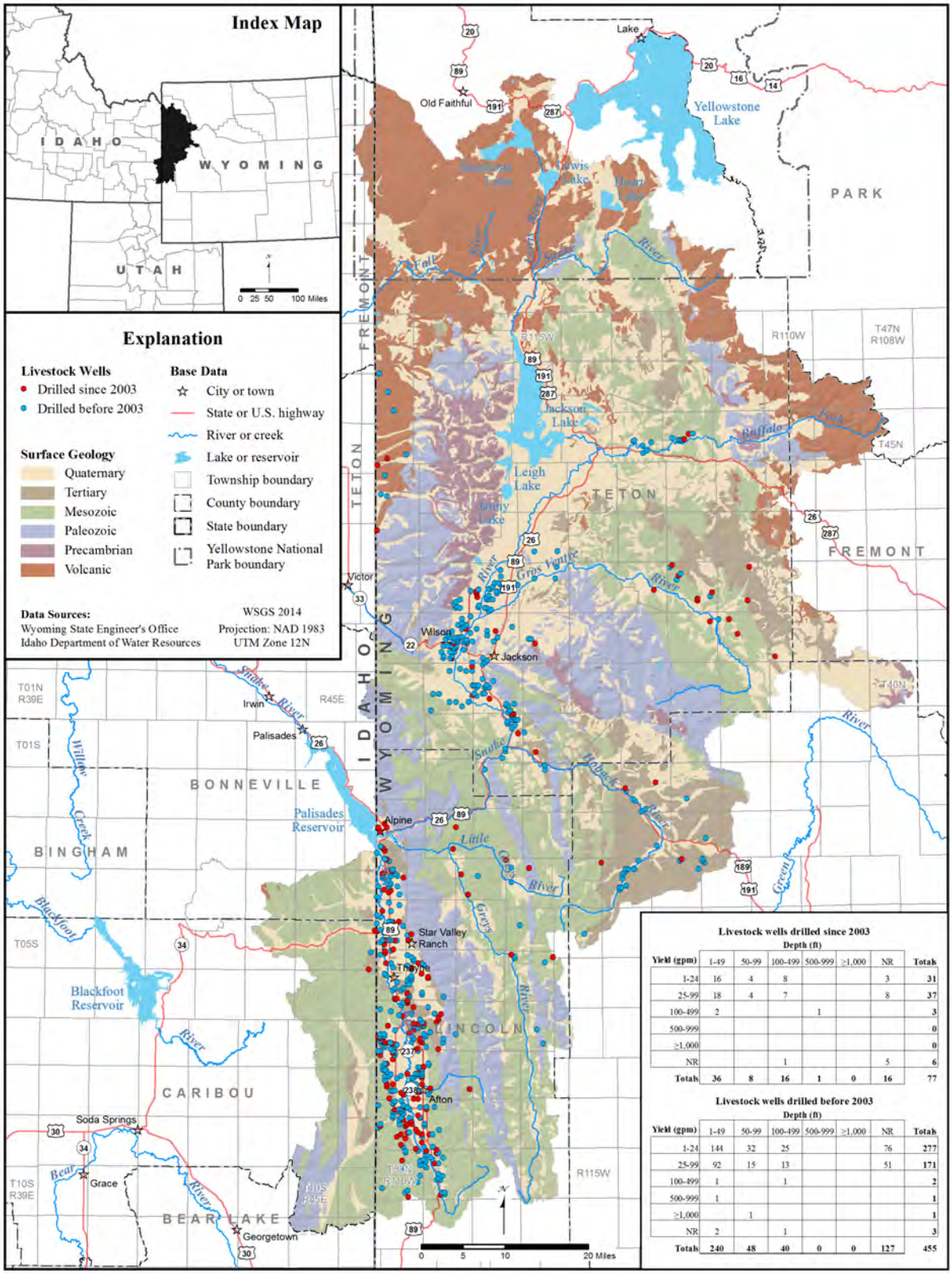
Irrigation wells drilled since 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99	4	1				1	6
100-499	7						7
500-999	2	1					3
≥1,000							0
NR						1	1
Totals	**13**	**2**	**0**	**0**	**0**	**2**	**17**

Irrigation wells drilled before 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99	4	1					5
100-499	12		2				14
500-999	1					2	3
≥1,000	2	1	1				4
NR	2						2
Totals	**21**	**2**	**3**	**0**	**0**	**2**	**28**

Figure 8-1. Wyoming SEO and Idaho DWR permitted and drilled irrigation wells, Snake/Salt River Basin.



Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	16	4	8			3	31
25-99	18	4	7			8	37
100-499	2			1			3
500-999							0
≥1,000							0
NR			1			5	6
Totals	**36**	**8**	**16**	**1**	**0**	**16**	**77**

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	144	32	25			76	277
25-99	92	15	13			51	171
100-499	1		1				2
500-999	1						1
≥1,000		1					1
NR	2		1				3
Totals	**240**	**48**	**40**	**0**	**0**	**127**	**455**

Figure 8-2. Wyoming SEO and Idaho DWR permitted and drilled livestock wells, Snake/Salt River Basin.

before and after January 2003. Most irrigation wells are located in rural areas and along rivers and other surface drainages where Quaternary 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 irrigation well permits that list depth were permitted for depths of less than fifty feet, across a wide range of yields for both total permits and permits issued since January 2003. **Tables 8-6** and **8-7** and the matrix tables in **figure 8-1** illustrate that most irrigation permits in the Snake/Salt River Basin were issued before 2003. **Figure 8-1** illustrates that most permits appropriate water from wells located near the Snake/Salt River, likely targeting alluvial deposits adjacent to the river.

8.6.3.4 Livestock use permits

Tables 8-6 and **8-7** show that 211 SEO permits and two IDWR groundwater permits have been issued solely for livestock use (STK) in the Snake/Salt River Basin. **Figure 8-2** shows the distribution of likely drilled stock wells in the Snake/Salt River Basin issued before and after January 2003. Stock wells are located throughout the basin, especially along the Snake and Salt rivers and tributary streams. Although, most stock wells are completed in Quaternary hydrogeologic units, some are completed in outcrops of Tertiary to Mesozoic aquifers and confining units located in areas along the uplands. The depth vs. yield tables on **figure 8-2** show that the largest number of total permits and permits issued since 2003 are for depths of one hundred feet or less and for yields of up to one hundred gpm. Many permits for stock watering have no recorded depth information.

8.6.3.5 SEO Municipal use permits

Tables 8-6 and **8-7** show that all 21 groundwater permits issued solely for municipal use (MUN) in the Snake/Salt River Basin are located in Wyoming. **Figure 8-3** shows the spatial distribution of likely drilled municipal wells. Most municipal permits do contain depth data. No municipal-use permits were listed in the IDWR data.

Tables 8-8 and **8-9** distinguish 31 municipal use groundwater permits on file with the SEO by status. **Table 8-8** summarizes selected information on twenty municipal-use permits that have been fully adjudicated. **Table 8-8** includes available information on permitted yield, well depth, depth of the producing interval, and the producing hydrogeologic unit. Six of the permits in **table 8-8** are for multiple uses. Because the "fully adjudicated" permit status indicates that the well has been inspected, the information in **table 8-8** is presumed to be fairly accurate. The wells in **Table 8-8** produce water from alluvial and bedrock aquifers (**pl. 2**). Information on producing intervals was obtained from SWAP data, WWDC consultant reports, and SEO data.

Table 8-9 summarizes selected information on eleven SEO municipal well permits listed as incomplete or that do not have a status listed. **Table 8-9** includes available information on permitted yield and well depth. Four of the permits in **table 8-9** are for multiple uses. The wells in **table 8-9** produce water from alluvial and bedrock aquifers (**pl. 2**).

While cancelled permits may or may not be associated with a completed well, abandoned status generally refers to a previously existing well.

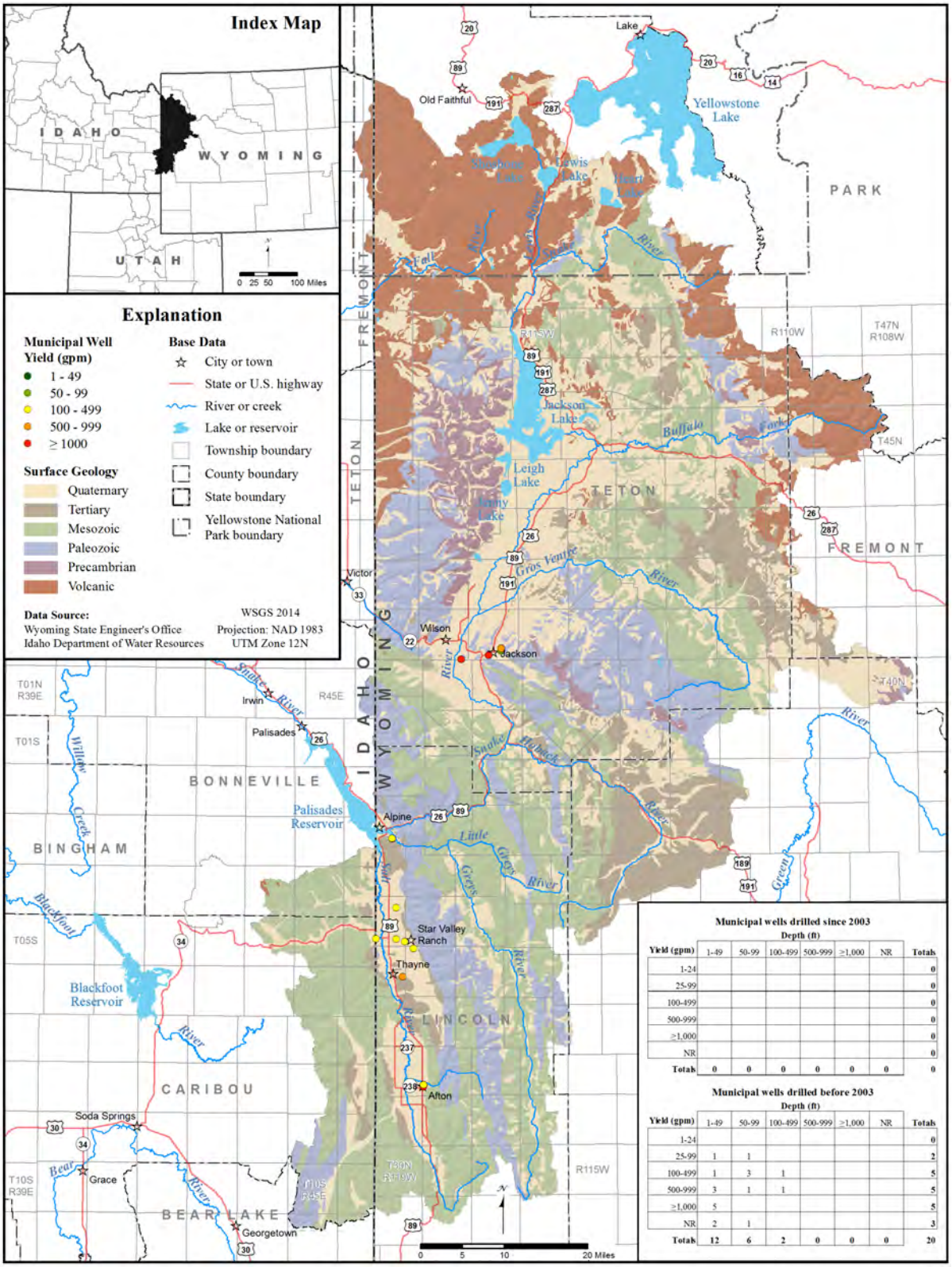
8.6.3.6 Domestic use permits

Domestic water withdrawals include non–community public water systems and rural domestic users. **Tables 8-6** and **8-7** show that groundwater permits for domestic use (DOM) outnumber permits for all other uses combined, with 3,751 SEO permits, and 48 IDWR permits.

Figure 8-4 shows the distribution of likely drilled domestic-use permits in the entire Snake/Salt River Basin issued before and after January 2003. Most domestic wells are located in rural areas, generally outlying population centers along rivers and other surface drainages. Most wells are completed in Quaternary and Tertiary geologic units. The depth vs. yield tables on **figure 8-4** show that basinwide, the largest percentage of permits issued before and since January 2003 allow well depths up to 499

Table 8-8. SEO fully adjudicated municipal well permits in the Snake/Salt River Basin.

Municipality or Community	Well Name	WSEO Permit Number	Permit yield (gpm)	Well Depth (feet)	Hydro-geologic unit	Multi-use	Depth of Producing Interval (feet)
Afton	AFTON WELL #1	P86364.0W	900	156	Salt Lake Formation		200-317
Afton	ENL AFTON WELL #1	P91531.0W	200	156			200-317
Alpine	ALPINE WATER DISTRICT #1	P39163.0W	200	60	Alluvium		180-265
Alpine	ALPINE WATER & SEWER DISTRICT WELL #2	P77717.0W	375	85.5	Alluvium		147-243
Alpine	ENL ALPINE WATER DISTRICT #1	P78067.0W	100	60			180-265
Alpine	ENL ALPINE WATER DISTRICT #1 WELL	P98662.0W	50	60			180-275
Jackson	JACKSON WELL #6	P101360.0W	1250	6.6	Alluvium/Colluvium	yes	7-81
Jackson	JACKSON WELL #7	P101361.0W	1250	5.8	Alluvium/Colluvium	yes	6-80
Jackson	JACKSON WELL #8	P101362.0W	1250	5.5	Alluvium/Colluvium	yes	6-81
Jackson	1ST ENL JACKSON WATER WELL #1	P104232.0W	0	54.5	Alluvium/Colluvium	yes	50-160
Jackson	3RD ENL JACKSON WATER WELL #2	P104233.0W	0	38.34	Alluvium/Colluvium	yes	60-165
Jackson	2ND ENL JACKSON WATER WELL #3	P104234.0W	0	27	Alluvium/Colluvium	yes	75-95
Jackson	JACKSON WATER WELL #1	P1385.0W	950	54.5			50-160
Jackson	JACKSON WATER WELL #2	P1386.0W	700	38.34			60-165
Jackson	JACKSON WATER WELL #3	P1945.0W	700	27			75-95
Jackson	ENL JACKSON WATER WELL #2	P2055.0W	950	38.34			60-165
Jackson	JACKSON #5	P69746.0W	2500	5			82-147
Jackson	ENL JACKSON WATER WELL #2	P85495.0W	100	45			185-195
Jackson	ENL JACKSON WATER WELL #3	P85496.0W	75	33			70-100
Thayne	THAYNE PHASE I WELL	P130958.0W	1000	27.7	Salt Lake Formation		28-310



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

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99	1	1					2
100-499	1	3	1				5
500-999	3	1	1				5
≥1,000	5						5
NR	2	1					3
Totals	12	6	2	0	0	0	20

Figure 8-3. Wyoming SEO and Idaho DWR permitted and drilled municipal wells, Snake/Salt River Basin.

Table 8-9. Incomplete, cancelled, abandoned, and unlisted SEO municipal well permits in the Snake/Salt River Basin.

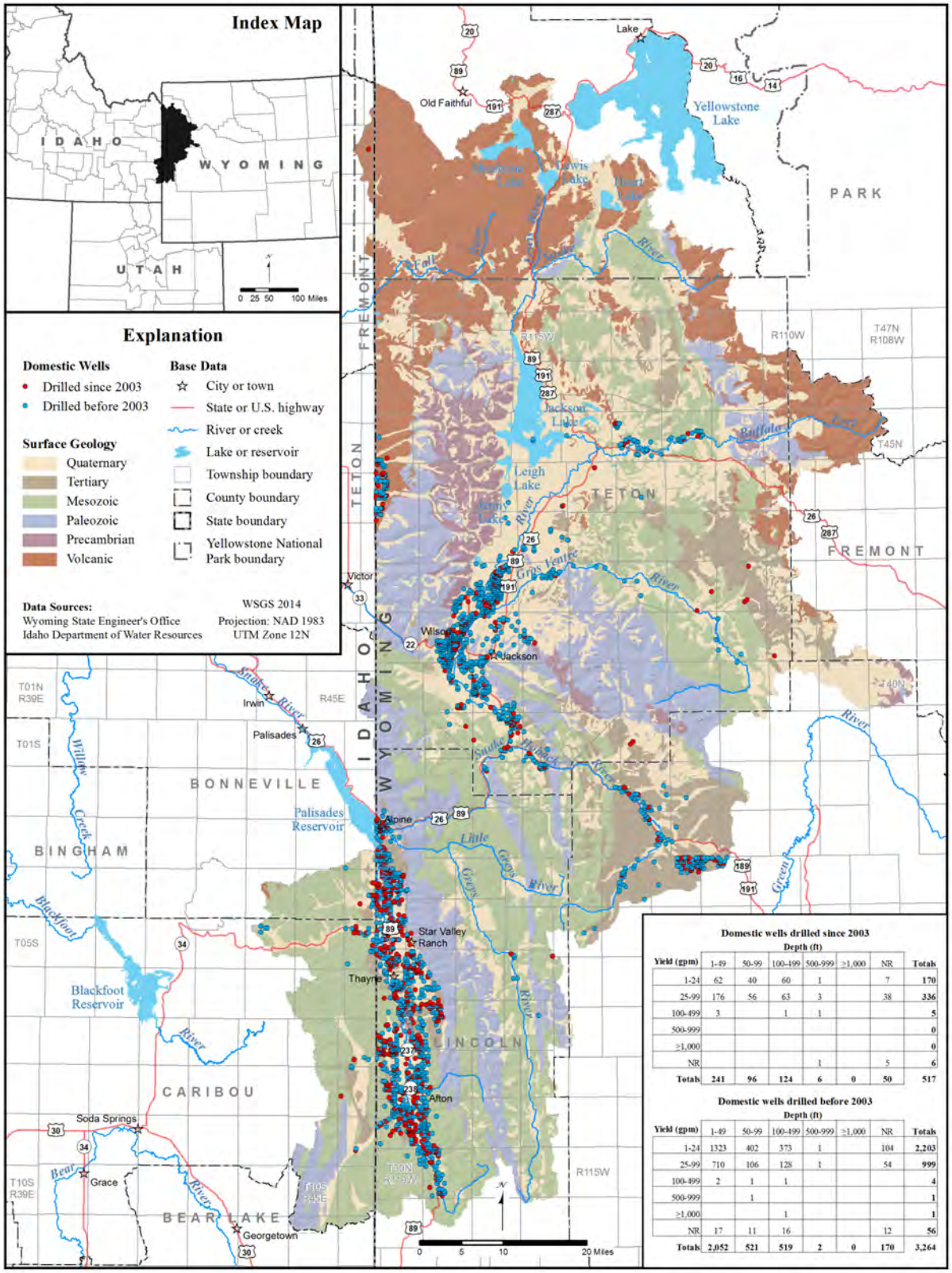
Municipality or Community	Well Name	WSEO Permit Number	Permit Yield (gpm)	Well Depth (feet)	Permit Status	New since 2005?	Multiple Use Well
Afton	AFTON EAST ALLEY WELL	P172886.0W	1200			Yes	
Alpine	3RD ENL ALPINE NO. 1 WELL	P189882.0W	350		Incomplete	Yes	
Alpine	1ST ENL ALPINE NO. 2 WELL	P189883.0W	325		Incomplete	Yes	
Etna	ETNA WELL NO. 1	P139351.0W	350	212	Incomplete		Yes
Freedom	FREEDOM #2	P101707.0W	400	67	Incomplete		Yes
Freedom	FREEDOM PIPELINE WELL #1	P396.0G	500	6	Incomplete		
Jackson	1ST ENL JACKSON WATER WELL #5	P104235.0W	0	5	Incomplete		Yes
Jackson	2ND ENL. JACKSON WATER WELL # 1	P142426.0W	500				Yes
Jackson	3RD ENL. JACKSON, TOWN OF	P146696.0W	925				
Star Valley Ranch	TSVR NO. 2	P193033.0W	300	178	Incomplete	Yes	
Star Valley Ranch	TSVR NO. 3	P193487.0W	500		Incomplete	Yes	

feet and yields up to 99 gpm. Many domestic use permits do not provide any recorded depth information.

8.6.3.7 Source Water Assessment Program (SWAP) wells and springs

The SWAP, a component of the federal Safe Drinking Water Act, is designed to help states protect public water systems (PWS) 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 (WHP) for groundwater PWS. A source-water assessment entails determining the source-water contributing area, inventorying potential sources of contamination to the PWS, determining the susceptibility of the PWS 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. 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/SWPWHP/SWAP_FAQs.

Table 8-10 provides SEO water right permit number, yield, producing unit and depth data for 135 SWAP wells in the Snake/Salt 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, volcanic, Cretaceous, and Paleozoic units are also identified as producing units in **table 8-10**. **Figure 5-11** shows the geospatial distribution of SWAP wells in the Snake/Salt River Basin and their relative susceptibility to potential contaminants.



Domestic wells drilled since 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	62	40	60	1		7	170
25-99	176	56	63	3		38	336
100-499	3		1	1			5
500-999							0
≥1,000							0
NR				1		5	6
Totals	**241**	**96**	**124**	**6**	**0**	**50**	**517**

Domestic wells drilled before 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1323	402	373	1		104	2,203
25-99	710	106	128	1		54	999
100-499	2	1	1				4
500-999		1					1
≥1,000			1				1
NR	17	11	16			12	56
Totals	**2,052**	**521**	**519**	**2**	**0**	**170**	**3,264**

Figure 8-4. Wyoming SEO and Idaho DWR permitted and drilled domestic wells, Snake/Salt River Basin.

Table 8-10. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply in the Snake/Salt River Basin.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
Town of Afton						
	AFTON, BOARD OF PUB UTILILTIES	5600002-102	P86364W	311	Well	Salt Lake Fm
	AFTON, BOARD OF PUB UTILILTIES	5600002-104		0	Well	Salt Lake Fm
	AFTON, BOARD OF PUB UTILILTIES	5600002-101	P7010E	0	Spring	Madison Limestone
	AFTON, BOARD OF PUB UTILILTIES	5600002-103	P65653W	126	Well	Salt Lake Fm
Town of Alpine						
	ALPINE, TOWN OF	5600156-101		0	Spring	Teewinot Fm
	ALPINE, TOWN OF	5600156-102	P77717W	243	Well	Alluvium
	ALPINE, TOWN OF	5600156-103	P39163W	275	Well	Alluvium
Town of Jackson						
	JACKSON, TOWN OF	5600213-105	P101360W	81	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-107	P101362W	81	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-106	P101361W	81	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-104	P104235W	147	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-101	P104232W	201	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-102	P104233W	200	Well	Alluvium/ Colluvium
	JACKSON, TOWN OF	5600213-103	P104234W	200	Well	Alluvium/ Colluvium
Wells without known Municipality						
	None listed	5601456-101	P65653W	0	Well	
	None listed	5600721-101	P11180W	20	Well	
	None listed	5600802-101	P54660	0	Well	
	None listed	5601253-101	P90673W	245	Well	Alluvium
	None listed	5680109-101	P26143W	101	Well	Alluvium
	None listed	5680117-101		36	Well	

Table 8-10. cont.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	ASPENS WATER & SEWER DISTRICT	5600220-103		100	Well	Alluvium/ Colluvium
	ASPENS WATER & SEWER DISTRICT	5600220-104	P101920W	95	Well	Alluvium/ Colluvium
	ASPENS WATER & SEWER DISTRICT	5600220-102	P101921W	152	Well	Alluvium/ Colluvium
	ASPENS WATER & SEWER DISTRICT	5600220-101	P101923W	109	Well	Alluvium/ Colluvium
	BAR J CHUCKWAGON	5600886-101	P40479W	60	Well	
	BEDFORD WATER & SEWER DISTRICT	5600006-103	P81829W	350	Well	Salt Lake Fm
	BEDFORD WATER & SEWER DISTRICT	5600006-101		0	Spring	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Fm and Flathead Sandstone
	BEDFORD WATER & SEWER DISTRICT	5600006-102		0	Spring	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Fm and Flathead Sandstone
	BRIDGER-TETON NF ATHERTON CR	5680207-102	P65736W	105	Well	
	BRIDGER-TETON NF HOBACK CG	5680139-101	P19402	0	Well	
	BRIDGER-TETON NF TURPIN MEADOW	5680210-101	P71623W	135	Well	
	BUFFALO VALLEY WATER DISTRICT	5600435-101	P120244W	155	Well	Unnamed ss fm and Bacon Ridge ss
	BUFFALO VALLEY WATER DISTRICT	5600435-102	P77006W	93	Well	Unnamed ss fm and Bacon Ridge ss
	CONTINENTAL INVESTMENTS OF WY, LLC	5601258-101	P101733W	131	Well	Alluvium

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	COWBOY VILLAGE RESORT	5600501-102		250	Well	Glacial Deposits
	COWBOY VILLAGE RESORT	5600501-101		150	Well	Glacial Deposits
	COWBOY VILLAGE RESORT	5600501-103		0	Spring	Glacial Deposits
	COWBOY VILLAGE RESORT	5600501-104		0	Spring	Glacial Deposits
	COWBOY VILLAGE RESORT	5600501-105		0	Spring	Glacial Deposits
	COWBOY VILLAGE RESORT	5600501-106		0	Spring	Glacial Deposits

Table 8-10. cont.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	C-V RANCHES (BOCES REG V)	5600806-101	P53100W	120	Well	Terrace
	C-V RANCHES (BOCES REG V)	5600806-102	P53848W	120	Well	Terrace
	DORNAN`S MOOSE ENTERPRISES	5601261-101	P89284W	85	Well	Terrace
	DORNAN`S MOOSE ENTERPRISES	5601261-102	P89286W	90	Well	Terrace
	ELK REFUGE INN	5600999-101		990	Well	Alluvium/ Colluvium
	ELKHORN BAR	5600528-101	P80633W	32	Well	
	ELKHORN BAR	5600528-103	P80633	32	Well	Madison Ls, Darby Fm, Bighorn Dolomite, Gallatin Ls, Gros Ventre Fm, Flathead Ss
	ETNA WATER & SEWER DISTRICT	5600157-101		0	Spring	Madison Ls, Darby Fm, Bighorn
	ETNA WATER & SEWER DISTRICT	5600157-102		0	Spring	Dolomite, Gallatin Ls, Gros Ventre Fm, Flathead Ss
	ETNA WATER & SEWER DISTRICT	5600157-103	P92269W	400	Well	Salt Lake Fm
	EVANS MOBILE HOME COURT	5600215-101	P20371W	70	Well	Snake River Alluvium
	EVANS MOBILE HOME COURT	5600215-102	P61731W	60	Well	Snake River Alluvium
	EVANS MOBILE HOME COURT	5600215-103	P42289W	75	Well	Snake River Alluvium
	FAIRVIEW WATER & SEWER DIST.	5600166-101	P93172W	418	Well	Salt Lake Fm
	FISH CREEK CENTER	5601412-101	P108620W	651	Well	Alluvium
	FISH CREEK INN	5600903-101	P29179W	58	Well	
	FLAT CREEK MOTEL	5601186-101	P76783	111	Well	Alluvium/ Colluvium
	FLAT CREEK RV PARK	5601273-101	P99707W	40	Well	
	FLYING SADDLE LODGE	5600604-101	P101241W	163	Well	
	FREEDOM WATER & SEWER DISTRICT	5600158-101	P396G	0	Well	
	GRAND TARGHEE RESORT	5601201-103	P40451W	700	Well	Madison Limestone
	GRAND TARGHEE RESORT	5601201-101	P3373W	676	Well	Madison Limestone
	GRAND TETON NP CLIMBERS RANCH	5680094-101		88	Well	terrace

Table 8-10. cont.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	GRAND TETON NP COLTER BAY	5680095-102	P30080W	175	Well	terrace
	GRAND TETON NP COLTER BAY	5680095-101	P842W	201	Well	terrace
	GRAND TETON NP ENV ED CENTER	5680099-101		10	Well	Alluvium
	GRAND TETON NP FLAGG RANCH	5680097-102		100	Well	Terrace
	GRAND TETON NP FLAGG RANCH	5680097-101		95	Well	Glacial Deposits
	GRAND TETON NP GROS VENTRE CG	5680100-101	P1377W	150	Well	Terrace
	GRAND TETON NP HIGHLANDS	5680101-101	P26142W	151	Well	Terrace
	GRAND TETON NP JACKSON LK LDGE	5680103-101	P30080W	250	Well	terrace
	GRAND TETON NP JENNY LAKE CAB	5680156-101	P142C	150	Well	Terrace
	GRAND TETON NP JENNY LAKE LODG	5680157-101		376	Well	terrace
	GRAND TETON NP LEEKS LODGE	5680105-101		131	Well	Glacial Deposits
	GRAND TETON NP LIZARD CRK CG	5680106-101	P865W	101	Well	Newcastle Sandstone
	GRAND TETON NP MOOSE BEAVER CK	5680093-102	P130045W	160	Well	terrace
	GRAND TETON NP MOOSE BEAVER CK	5680093-101	P130046W	160	Well	terrace
	GRAND TETON NP MORAN BFLO RNGR	5680107-101	P149068W	38	Well	Terrace
	GRAND TETON NP S.JENNY LAKE WS	5680096-101	P141G	250	Well	terrace
	GRAND TETON NP SIGNAL MTN	5680108-101		260	Well	Glacial Deposits
	GRAND TETON NP TRIANGLE X RANC	5680110-101		0	Spring	Glacial Outwash
	GROS VENTRE GRILL	5601227-101	P22750W	33	Well	Alluvium/ Colluvium
	GROS VENTRE RIVER RANCH	5601406-101	P84656W	0	Well	

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	GROS VENTRE UTILITY	5600027-102	P76095W	151	Well	Terrace
	GROVER WATER & SEWER DISTRICT	5600160-101	P93173W	300	Well	Salt Lake Fm

Table 8-10. cont.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	GROVER WATER & SEWER DISTRICT	5600160-102	P56049W	250	Well	Salt Lake Fm
	GROVER WATER & SEWER DISTRICT	5600160-103	P18543D	0	Spring	Nugget SS or Ankareh Fm
	HATCHET CAFE & MOTEL	5600517-103	P72854W	65	Well	
	HOBACK VILLAGE	5600695-101	P29305W	25	Well	Alluvium
	JACKSON HOLE AIRPORT	5600844-101	P86871W	143	Well	
	J-W SUBDIVISION	5600877-102	P77828W	260	Well	Bear River Fm
	J-W SUBDIVISION	5600877-103	P60074W	175	Well	Bear River Fm
	KENNINGTON SPRINGS PIPELINE	5601199-101		0	Spring	Stump fm, Preuss sandstone or redbeds and twin creek limestone
	LAZY J CORRAL	5600347-102	P82575W	95	Well	
	LAZY J CORRAL	5600347-101	P91530W	300	Well	
	LONE EAGLE RESORT	5601264-101	P104732W	500	Well	Bear River Fm
	LOWER VALLEY ENERGY	5601403-101	P52035W	360	Well	Alluvium
	MAVERICK STATION	5600882-101		0	Well	Alluvium
	MOUNTAIN INN MOTEL	5601150-101	P20372W	280	Well	Salt Lake Fm.
	NATIONAL WILDLIFE ART MUSEUM	5601325-101	P89598W	186	Well	
	NORDIC RANCHES PROPERTY ASSOC.	5601418-102	P108464W	550	Well	Bighorn Dolomite
	NORDIC RANCHES PROPERTY ASSOC.	5601418-101	P100147W	360	Well	Bighorn Dolomite
	NORTH ALPINE IMPROVEMENT & SERVICE DIST	5601021-101	P102467W	109	Well	
	OSMOND PIPELINE CO	5600154-101	P72735W	0	Spring	Nugget Sandstone
	R LAZY S RANCH	5600499-101	P71244W	63	Well	Terrace
	R LAZY S RANCH	5600499-102	P79922W	60	Well	Terrace
	RAFTER J SUBDIVISION HO ASSN	5600822-101	P93364W	100	Well	Alluvium/ Colluvium
	RAFTER J SUBDIVISION HO ASSN	5600822-102	P48096W	100	Well	Alluvium/ Colluvium
	SNAKE RIVER PARK, INC.	5600519-101	P51149W	100	Well	
	SO. PARK VILLAGE SUBD	5600836-101	P4842P	212	Well	Alluvium/ Colluvium

Table 8-10. cont.

MUNICIPALITY	Well Name	Public Water System ID	WSEO Permit No.	Well Depth (ft)	Source Type	Producing Unit
	SPOTTED HORSE RANCH	5600492-101		65	Well	Alluvium
	SPOTTED HORSE RANCH	5600492-102		65	Well	Alluvium
	SPOTTED HORSE RANCH	5600492-103		65	Well	Alluvium
	SPRING CREEK IMP DIST.	5600811-101	P96458W	123	Well	
	STAR VALLEY RANCH ASSOCIATION	5600287-104	P112167W	380	Well	Salt Lake Fm
	STAR VALLEY RANCH ASSOCIATION	5600287-103	P90328W	460	Well	Salt Lake Fm
	STAR VALLEY RANCH ASSOCIATION	5600287-102	P28134W	0	Spring	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Fm, Flathead Sandstone
	STAR VALLEY RANCH ASSOCIATION	5600287-101	P112130W	0	Spring	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Fm, and Flathead Sandstone
	STAR VIEW ESTATES	5600893-101	P56978W	168	Well	Salt Lake Fm
	TARGHEE NF TRAIL CREEK CAMPGRD	5680116-101		0	Well	
	TETON GABLES	5601152-101	P10299	0	Well	
	TETON SHADOWS HOME OWNERS ASSN	5600724-101	P76779W	31	Well	terrace
	TETON VALLEY RANCH CAMP	5600524-101	P15156W	196	Well	Alluvium
	TETON VALLEY RANCH CAMP	5600524-102	P15158P	60	Well	Alluvium
	TETON VILLAGE KOA	5600520-101	P15658W	62	Well	
	TETON VILLAGE WTR & SWR DIST.	5600218-102	P100143W	170	Well	Alluvium/ Colluvium
	TETON VILLAGE WTR & SWR DIST.	5600218-101	P100142W	164	Well	Alluvium/ Colluvium
	THAYNE, TOWN OF	5600159-101		0	Spring	Salt Lake Fm
	THAYNE, TOWN OF	5600159-102	P130958W	272	Well	Salt Lake Fm
	VIRGINIAN LODGE	5600684-101	P1566W	150	Well	
	VISTA GRANDE	5600683-101	P42529W	70	Well	
	WY TRANS DEPT STAR VALLEY RA	5600952-102	P115323W	50	Well	Terrace
	WY TRANS DEPT STAR VALLEY RA	5600952-101	P51918W	325	Well	Salt Lake Fm
	YELLOWSTONE NP LEWIS LAKE CG	5680081-101		139	Well	Rhyolite flows, tuff, and intrusive igneous rock

8.6.3.8 Industrial use

Table 8-6 lists seven SEO permits for industrial (IND) use; only one industrial use permit is listed for Idaho in the Snake/Salt River Basin. Primary industrial uses in the Snake/Salt River Basin have included construction companies and aggregate and gravel mining. The SEO database does not identify specific industrial uses; individual permit summaries must be reviewed for that information. **Figure 8-5** shows the distribution of likely drilled industrial use permits in the entire Snake/Salt River Basin issued before and after January 2003.

8.6.3.8.1 Oil and gas production, injection wells and WYPDES outfalls

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, while 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. Information on currently produced water associated with conventional oil and gas operations was obtained from the WOGCC website: http://wogcc.state.wy.us/.

Figure 5-4 shows the locations of conventional oil and gas infrastructure in the Snake/Salt River. WOGCC records show that all oil and gas wells in the Snake/Salt River Basin are plugged and abandoned and that no production has occurred during the last three decades (**table 8-1b**; WOGCC, 2013). There is, however, a gas pipeline that runs from the northern Green River Basin to Jackson. **Figure 5-5** shows the locations of Class V and other injection wells, in the Snake/Salt River Basin. The WDEQ permits Class V wells for disposal of non-hazardous wastewaters from a variety of sources. Most injection permits in the basin are for Class V facilities used for heat pump return flows and the disposal of septic and storm water effluents.

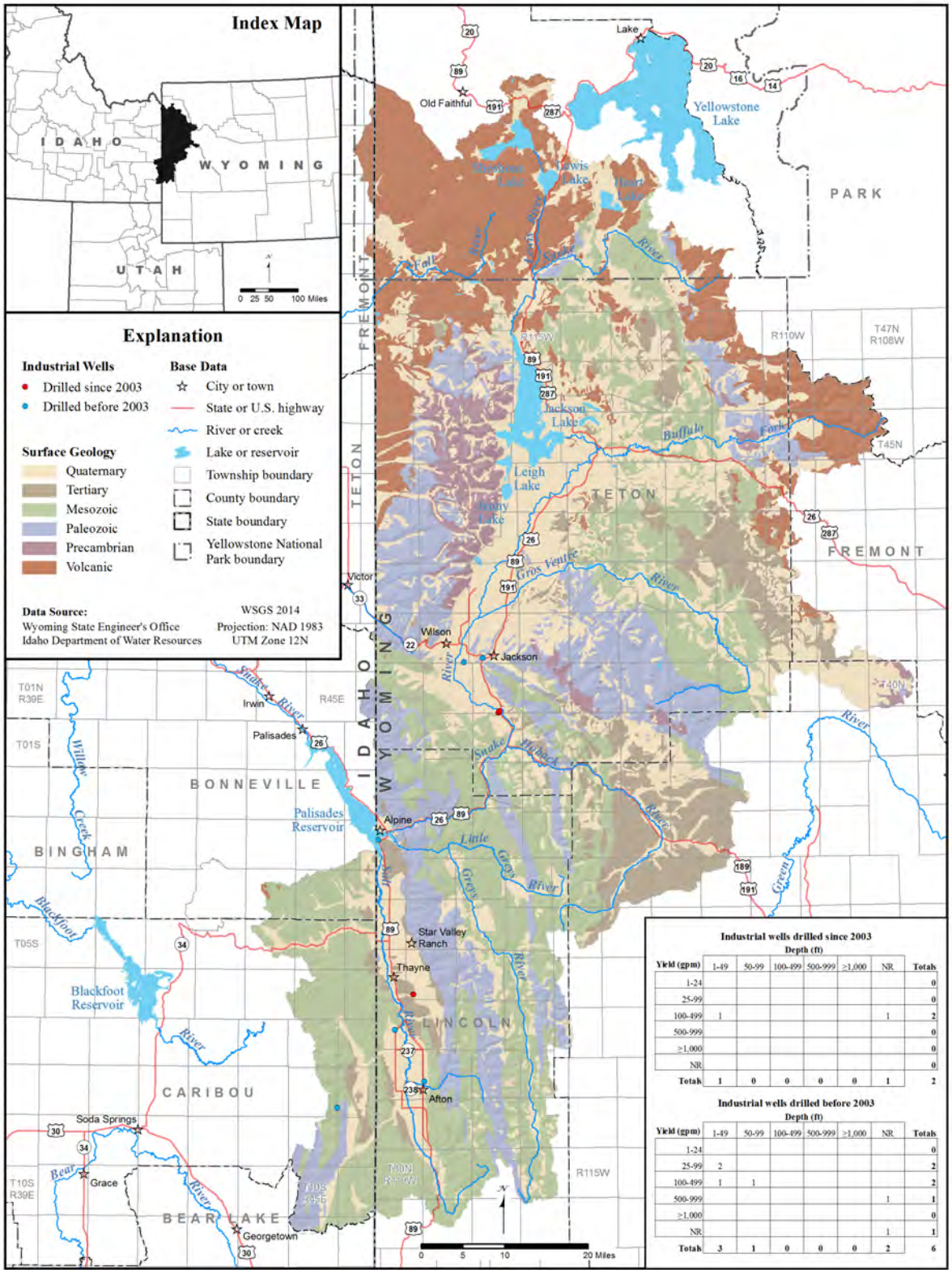
Figure 5-6 shows the location of WYPDES outfalls and WDEQ groundwater pollution control facilities.

Effluent waters from various facilities of suitable quality can be put to beneficial use (e.g., stock watering, agriculture, drilling, and industrial dust suppression). Otherwise, effluent water is primarily discharged to the surface under the regulation of WDEQ NPDES/WYPDES permits. WDEQ data indicates that most WYPDES permits in the Snake/Salt River Basin are issued for municipal wastewater lagoons for the towns of Jackson and Thayne. Estimates of the volume of produced water discharged in the Snake/Salt River Basin under the WYPDES program are not readily available.

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 effluent water management strategy involves some consumptive losses to evapotranspiration. On the other hand, injecting effluent 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. Effluent waters discharged to the surface under a WYPDES permit generally add to streamflows and increase the growth of vegetation. The water balance developed within this study did not consider effluent water on either side of the equation.

8.6.3.8.2 Groundwater use for non-energy minerals development

Groundwater withdrawals for non-energy minerals development in the Snake/Salt River Basin are primarily associated with sand, gravel, and limestone production. **Figure 5-8** shows the locations of groundwater permits for these uses in the Snake/Salt River Basin. Mining permits can be viewed on WDEQ Land Quality Division website: http://deq.state.wy.us/lqd_permit_public/.



Industrial wells drilled since 2003

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					1	2
500-999							0
≥1,000							0
NR							0
Totals	**1**	**0**	**0**	**0**	**0**	**1**	**2**

Industrial wells drilled before 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99	2						2
100-499	1	1					2
500-999						1	1
≥1,000							0
NR						1	1
Totals	**3**	**1**	**0**	**0**	**0**	**2**	**6**

Figure 8-5. Wyoming SEO and Idaho DWR permitted and drilled industrial wells, Snake/Salt River Basin.

8.6.3.9 Monitoring wells

Table 8-6 lists 677 SEO groundwater permits for monitoring wells in the Wyoming part of the Snake/Salt River Basin; **table 8-7** shows thirty monitoring wells in Idaho. 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., an underground fuel storage tank) or to monitor for groundwater impacts from various activities (e.g., mining or waste management). When used for monitoring alone, these wells have no permitted yield; however, there may be a permitted yield for other, secondary uses. The SEO required permits for monitoring wells of four inches or less in diameter only through 2004; therefore, the data for these permits are incomplete.

Figure 8-6 shows the distribution of likely drilled SEO monitoring well permits in the Snake/Salt River Basin and permits issued before and after January 2003. Most monitoring wells are located in alluvial units near Jackson or in the Salt River Valley. The depth vs. yield tables on **figure 8-6** show that while permits have been issued for all depth categories, by far the largest number were issued for depths up 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, only nine well permits include recorded yield data. Only 35 monitoring wells were permitted after 2003; however, as discussed above, this number is probably understated, per the 2004 SEO policy change.

8.6.3.10 Permits for other and miscellaneous uses

Table 8-6 indicates that 905 permits have been issued for "other" uses and 532 permits for "multi-use" wells have been granted by the SEO (**table 8-6**). Multi-use permits list more than one use; for example a permit that shows both "domestic and "stock" use is a multi-use permit. **Table 8-7** lists six IDWR permits for "other" wells and one "multi-use" permit issued by the IDWR. Some of the "multi-use" permits issued are for test wells generally employed for aquifer testing to determine aquifer characteristics. Information on specific miscellaneous use and test wells may be found in some permit applications available online. However, developing detailed information for specific miscellaneous use and test wells was beyond the scope of this study.

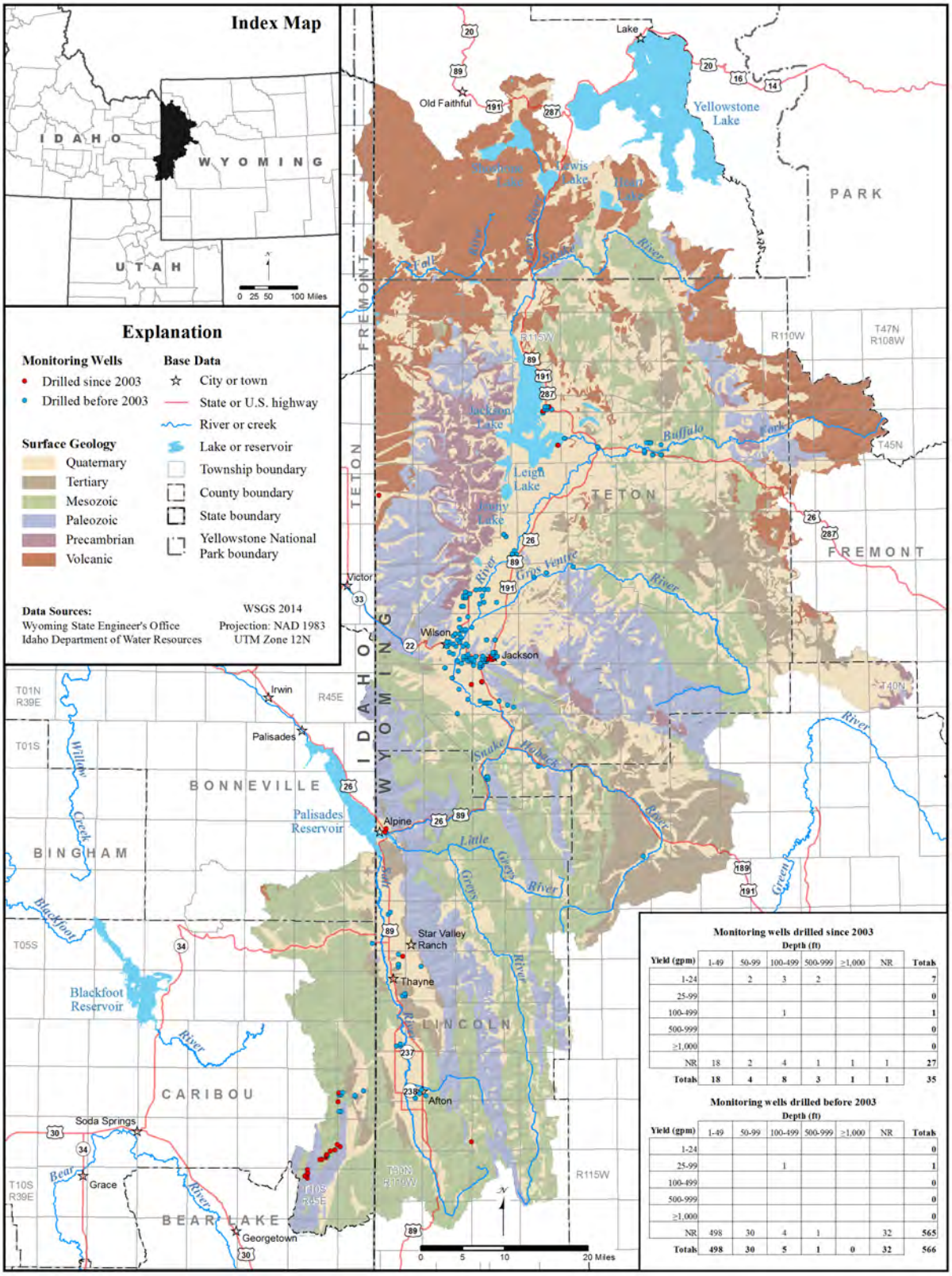
Figure 8-7 shows the distribution of likely drilled wells permitted for "miscellaneous use" and "other" wells in the Snake/Salt River Basin, and permits issued before and after January 2003. "Miscellaneous use" and "other" wells are located throughout the Snake/Salt River Basin and are generally concentrated along rivers and their larger tributaries. The depth vs. yield tables on **figure 8-7** show that most groundwater permits have been issued for depths up to 500 feet and for yields of one to 99 gpm for both total permits and permits issued since 2003. A fraction of these permits have no recorded depth.

8.6.3.11 Hydrothermal use

The geothermal resources of the Snake/Salt River Basin are of the high-low-temperature hydrothermal type, occurring where groundwater exists at anomalously elevated temperatures (relative to the average geothermal gradient). Although, the Yellowstone Plateau is characterized by major high- and low-temperature geothermal features. These occurrences are not typically found at a depth where they can be put to beneficial use. Hydrothermal resources of the Snake/Salt 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., Granite Hot Springs).

8.7 Groundwater interference/ interconnection with surface water

The potential for interference between wells and well fields located within areas of interconnected surface and groundwater that exhibit historically high levels of drawdown must be considered when assessing the historic, current, and future use of groundwater in the Snake/Salt River Basin. These issues, however, are not as significant in Snake/



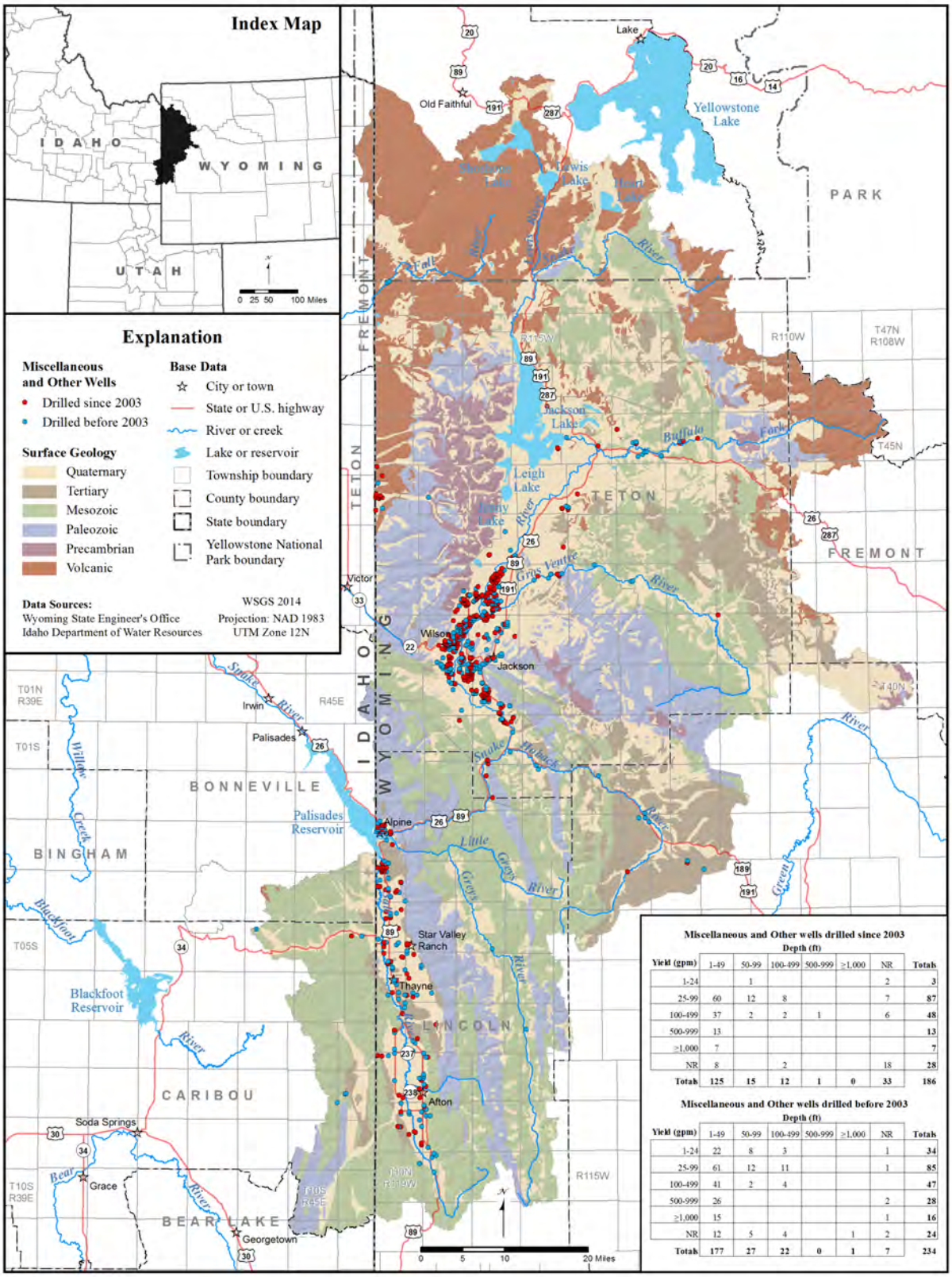
Monitoring wells drilled since 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24		2	3	2			7
25-99							0
100-499			1				1
500-999							0
≥1,000							0
NR	18	2	4	1	1	1	27
Totals	**18**	**4**	**8**	**3**	**1**	**1**	**35**

Monitoring wells drilled before 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99			1				1
100-499							0
500-999							0
≥1,000							0
NR	498	30	4	1		32	565
Totals	**498**	**30**	**5**	**1**	**0**	**32**	**566**

Figure 8-6. Wyoming SEO and Idaho DWR permitted and drilled monitoring wells, Snake/Salt River Basin.



Miscellaneous and Other wells drilled since 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24		1				2	3
25-99	60	12	8			7	87
100-499	37	2	2	1		6	48
500-999	13						13
≥1,000	7						7
NR	8		2			18	28
Totals	125	15	12	1	0	33	186

Miscellaneous and Other wells drilled before 2003

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	22	8	3			1	34
25-99	61	12	11			1	85
100-499	41	2	4				47
500-999	26					2	28
≥1,000	15					1	16
NR	12	5	4		1	2	24
Totals	177	27	22	0	1	7	234

Figure 8-7. Wyoming SEO and Idaho DWR permitted and drilled miscellaneous and other wells, Snake/Salt River Basin.

Salt River Basin compared to Wyoming's more arid river basins. The use of groundwater resources is not addressed in the Snake River Compact of 1949 (**appendix D**).

8.7.1 Interference between wells

As a well withdraws water from an unconfined aquifer, it depresses the groundwater level around the well casing in a generally radial configuration, called a "cone of depression". In areas where several actively pumping wells are sited in close proximity to each other, their respective cones of depression may overlap and "well interference" may result. If well interference becomes excessive, aquifer water levels may drop below the depth of some wells causing conflicts between users. In Wyoming, the SEO may address cases of excessive well interference by recommending the formation of a groundwater control area wherein groundwater uses are actively managed by a groundwater control area advisory board. According to Wyoming State Statute WSS 41-3-912, 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; and
- Other conditions exist or may arise that require regulation for the protection of the public interest.

Currently, there are no control areas designated in the Snake/Salt River Basin. Additional information about groundwater control areas can be found online at: https://sites.google.com/a/wyo.gov/seo/ground-water/groundwater-control-areas-advisory-boards.

8.7.2 Interconnection between groundwater and surface water

Surface flows are subject to strict water rights, and conflicts occur where groundwater extraction affects surface flow. Although the Wyoming Constitution establishes that all surface water and groundwater within Wyoming's borders is owned by the state, the right to put surface water and groundwater to beneficial use is permitted as water rights by the Wyoming SEO and adjudicated by the Wyoming Board of Control. Surface water resources are subject to interstate agreements that limit how much streamflow can be depleted before leaving the state. Furthermore, conflicts among users within the state or across state lines can occur where groundwater extraction may affect surface flows. Although interconnection between groundwater and surface water is not currently a significant water rights issue in the Snake/Salt River Basin, it could become a point of contention in the future as the basin's population grows.

To avert present and future conflicts over the allocation and use of water flows within the Snake/Salt River Basin, the states of Idaho and Wyoming agreed to the Snake River Compact in 1949. The compact controls surface flows in the Snake and Salt Rivers and tributary streams. The Interstate Streams Division of the SEO summarizes the provisions of the compact as follows:

> "The Compact recognizes, without restrictions, all existing rights in Wyoming as of the date of the Compact. It permits Wyoming unlimited use for domestic and stock uses provided that stock water reservoirs shall not exceed twenty ac-ft in capacity. It permits Wyoming to divert (or store) for new developments, either for supplemental or original supply, four percent of the Wyoming-Idaho state line flow of the Snake River.
>
> Use of the water is limited to diversions within the Snake River drainage basin unless both states agree otherwise.

> The Compact gives preference to domestic, stock and irrigation uses of the water over storage for the generation of power."

Appendix D (SEO, 2006) contains a copy of the Snake River Compact of 1949. The Interstate Streams Division of the SEO administers the provisions of the compact that fall under the authority of the state of Wyoming. Further information is available online at: https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/snake-river-basin.

Chapter 9

Looking to the Future

Karl Taboga and Paul Taucher

The purpose of this chapter is to discuss future water use opportunities in the Snake/Salt River Basin. This issue was examined in detail in previous Snake/Salt River Basin Water plans (Sunrise Engineering, 2003; Wyoming Water Development Office , 2014) and the Wyoming Framework Water Plan (WWC Engineering and others, 2007). This study provides the most current information available about the future focus and direction of Snake/Salt River Basin groundwater development projects.

The discussions of technical concepts and geology previously covered in this study provide the background required 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 summarized the hydrogeologic characteristics of the complex geologic settings in the Snake/Salt drainage. Future groundwater development in the Snake/Salt River Basin is physically limited by its complex hydrogeology. Specific groundwater development projects are discussed in **section 9.1**, and recommendations for future updates of this Groundwater Determination Technical Memoranda are presented in **section 9.2**.

Additional supporting information for the project assessments contained in this chapter can be found in previous chapters of this study:

- Basin hydrogeology is discussed at length in **chapters 5** through **7** and illustrated in **plates 4, 5**, and **6**.
- Groundwater chemical characteristics are summarized in **chapter 7** and **appendices E** through **F**.
- Recent and historic development patterns specified by beneficial use, obtained from the State Engineer's Office, are examined in **chapter 8**.
- Studies published by the USGS (**chapter 7**) and WWDO (**appendix B**) examine the development potential by specific aquifers.
- The 2003 Water Plan for the Snake/Salt River Basin (Sunrise Engineering, 2003), the 2012 Water Plan (WWDO, 2012) 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 (WRDS) library, specifically the WWDC Projects and Studies Web page, contains hundreds of water development reports for projects completed over the last forty years for localities throughout Wyoming.

This chapter only discusses development projects that are designed with the primary objective of producing potable groundwater. Projects that 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

- Water availability – A groundwater resource must be legally, economically, and physically available. In the semi-arid west, the significance of the last two factors cannot be overstated. Large sources of good quality groundwater exist in most Wyoming river basins but in many cases, they are located at such distances from population centers that development is uneconomic. In the Snake/Salt River Basin, there are few legal constraints on groundwater development and availability is controlled primarily by hydrogeology. Fortunately, most of the basin's communities are located in close proximity to productive alluvial aquifers.

- Funding – Groundwater development projects are expensive and most Wyoming municipalities lack the funds required

to plan, carry out, and complete development programs. Funding for some projects, therefore, has to be obtained from other governmental agencies. The primary water development funding agencies in Wyoming are the WWDC, DEQ, and the U.S. Department of Agriculture.

- Stakeholder involvement – The successful completion of any groundwater project requires the involvement of stakeholders who have interests in the development or preservation of a particular water resource. Stakeholders include current and future water users; landowners; business representatives; attorneys; scientists; engineers; environmental 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.

- Interstate compacts - The Snake River Compact of 1949 regulates surface water use only. The provisions of the compact are primarily administered by the SEO. Currently, there is no interstate regulation of groundwater use in the basin.

- 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 measures for others. For example, the National Primary Drinking Water Regulations (**table 5-1**) 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 fewer than 25 people. Nevertheless, water quality in private wells is frequently evaluated in comparison to the Maximum Contaminant Levels (MCL) contained in the EPA regulations.

- Environmental regulation – Water development projects in Wyoming are subject to regulation under the provisions of state and federal environmental laws including:
    - 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 plant and animal species. 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 (NEPA) – a main federal law that established national environmental policy. It requires federal agencies in the executive branch to write Environmental Impact Statements (EIS) and Environmental Assessments (EA) 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 projects in the Snake/Salt River Basin

Appendix B contains a chronological summary of groundwater development related projects sponsored by the WWDC in the Snake/Salt River Basin since 1973. Information contained in many of these studies was used to 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 Snake/Salt River Basin:

- References to the study(s) – full citations are included.
- Location including: town, county, rural area, irrigation district, well site, etc.
- Aquifers involved in the study.
- Descriptions of development project(s) and aquifer development potential.
- Summary of results; and
- Current project status.

9.1.2 Future water use opportunities

Technical Memorandum W of the 2003 Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) provides a detailed discussion of future water use opportunities that could expand water supplies to meet current and future demands. These water use opportunities were initially developed by the Snake/Salt River Basin Advisory Group (BAG) in 2002 and can be reviewed online at: http://waterplan.state.wy.us/BAG/snake/meetingrecord.html. The BAG list identifies promising structural and non-structural water development projects. 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. Structural opportunities 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 instead involve programmatic changes in water use and management such as water conservation programs, improvements in efficiency-of–use, water-banking, and improved reservoir operation.

Most of the opportunities discussed in Technical Memorandum W (Sunrise Engineering, 2003) involve structural improvement projects for surface water bodies. Groundwater projects include:

- Increase natural recharge in the Star Valley by routing spring runoff to existing storage sites such as gravel pits.
- Develop septic system management alternatives that would encourage the creation of regional wastewater systems to prevent groundwater pollution.
- Allow for the expansion of municipal water systems.
- Require metering of municipal and community water systems to encourage water conservation.

This report examines potential new groundwater development in the Snake/Salt River Basin by providing brief discussions of the development potential (**section 9.1.3**) of the basin's major aquifer systems and overviews of recent WWDC groundwater development projects (**section 9.1.4**).

9.1.3 Groundwater development potential by aquifer system

Unlike other Wyoming river basins such as the Platte (Taucher and others, 2013) and the Bear (Taboga and others, 2014), the issue of the hydraulic connection between surface and groundwater resources is not considered in the governing interstate compact. Thus, future groundwater development projects will be designed and completed based on the location and magnitude of future water demands,

Table 9-1. Generalized groundwater development potential for major regional aquifer systems in the Snake/Salt River Basin (modified from WWC Engineering and others, 2007; WWDO, 2014; chapter 7, this report).

Age	Center	Location	Well yields	Major aquifers	General potential for new development
Quaternary	Alluvial	Throughout Snake/ Salt River Basin	Small to large	Unconsolidated deposits	Good to very good
	Non-alluvial	Throughout Snake/ Salt River Basin	Small to moderate	Primarily unconsolidated terrace deposits but locally can include glacial deposits	Good to very good
	Volcanic Rocks	Yellowstone Volcanic Area and Northern Ranges	Small to moderate	Undifferentiated volcanic deposits	Fair to good – deposits generally located distant from population centers
Tertiary	Late	Scattered small outcrops from southern to east central basin	Small to large	Salt Lake, Teewinot	Fair to very good
	Early	Scattered small outcrops eastern basin	Small to moderate	Wind River, Wasatch	Fair - outcrops generally located distant from population centers
Mesozoic	Late Cretaceous	Widespread outcrops throughout basin	Small to moderate	Mesaverde, Frontier	Poor to fair – little yield data
	Early Cretaceous	Widespread outcrops throughout basin	Small to moderate	Thomas Fork	Fair to good - some marginal yields
	Triassic/Jurassic	Outcrops on uplands and flanks of south basin	Small to large	Twin Creek, Nugget	Fair to good –yield data from springs in Snake/Salt Basin
Paleozoic	Late	Widespread outcrops throughout basin	Small to very large	Madison, Tensleep, Wells	Fair to very good – some marginal water quality
	Early	Widespread outcrops throughout basin	Small to large	Flathead, Bighorn, Gallatin	Good – some marginal water quality

groundwater availability and quality, funding, stakeholder involvement, and environmental regulations. **Table 9-1** summarizes further groundwater development potential in the basin's main hydrogeologic units.

Virtually all aquifers and some confining units in the Snake/Salt River Basin have some physical potential for development (**pl. 2** and **table 9-1**), depending on the requirements for quantity, the quality required by the specified beneficial use(s), and technical limitations. The Quaternary Snake/Salt alluvial aquifer remains available for future groundwater development. Additionally, Mesozoic and Late Paleozoic bedrock aquifers are underutilized and may be prime targets for future development especially within or in close proximity to outcrop areas where recharge is actively occurring, residence times are low, and water quality is good. Although well yields could be expected to range from ten to five hundred gpm in these aquifers, water quality and susceptibility

to surface sources of contamination (e.g. irrigation return flows and leachates from septic systems) should be considered in evaluating development prospects.

9.1.4 Recent WWDO groundwater development prospects

An examination of WWDO groundwater development projects conducted since 2003 provides, perhaps, the most realistic evaluation of future groundwater development in the Snake/Salt 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 for new and additional public-support groundwater development in the Snake/Salt River Basin.

9.1.4.1 Afton

Sunrise Engineering (2006) conducted a Level II hydrogeologic evaluation of the Salt Creek alluvial aquifer. The investigation determined aquifer thickness and the depth to groundwater, installed a test well, and assessed groundwater quality. Subsequently, a new municipal water production well (East Alley Well) was sited and installed to a depth of 315 feet below ground surface in the Salt Creek alluvial aquifer. A constant discharge pump test indicated that the new well was capable of producing 1,230 gpm over a 41 hour period with approximately seven feet of drawdown. Water levels recovered completely within one minute of the cessation of pumping. All water quality constituents were well below EPA Maximum Contaminant Levels for drinking water or were non-detectable. Sunrise Engineering (year) recommended that a subsequent Level III design and construction project be completed to connect the new well to Afton's public water system.

9.1.4.2 Alpine

Rendezvous Engineering (2009) conducted a Level II study under contract to the WWDC to evaluate Alpine's existing water supply, demands, and facilities. At that time, Alpine's municipal water system drew water from two wells completed approximately 270 feet below ground surface in fractured limestone bedrock. A third municipal supply well was installed in the limestone aquifer in 2005 but required final completion. Maximum sustained pumping capacities for all three wells were estimated at 750 – 1,000 gpm. Rendezvous Engineering recommended that Alpine improve the existing public water system by installing larger pumps in the 2 older wells and completing the new well.

9.1.4.3 Alta

Rendezvous Engineering (2007) also completed a Level II study for the town of Alta that evaluated the existing public water system as well as present and future water demands. During the investigation, three test wells were installed and tested. Groundwater evaluations were conducted in the glacial/alluvial aquifer that provided municipal water supplies at that time and the underlying fractured volcanic bedrock aquifer. Recommendations for water system improvements included installing a larger pump in the existing municipal well (Targhee Town #1) and completing two of the test wells as municipal supply wells (Targhee Town #3 and #4).

9.1.4.4 Kennington Springs

Keller Associates (2003) conducted a Level I evaluation of the existing Kennington Springs water system and made recommendations to meet requirements imposed by future growth in the area. In 2003, an improved spring supplied adequate amounts of good quality water to area residents, and the transmission and distribution systems were in good condition. However, future water demands under moderate or high growth scenarios will require installation of at least one well, most likely in the Twin Creek aquifer.

9.1.4.5 North Alpine

Rendezvous Engineering (2009) conducted a Level II study for North Alpine that provided an evaluation of the existing water system, improvement alternatives, cost estimates, financing options and permitting requirements. The study concluded that the existing Salt Lake aquifer municipal wells provided adequate supplies of good quality water and that two new municipal wells could be sited in existing wellfield, as needed. The report noted that the existing transmission/distribution system required improvements and provided cost estimates.

9.1.4.6 Squaw Creek

WWDC funded a Level II study (AVI, 2012) to explore the feasibility of acquiring additional sources of supply for the Squaw Creek Water District. Currently, these water supplies are sourced from two wells completed in the Game Creek alluvium and a spring that discharges from the Squaw Creek Alluvium. The study concluded that the subdivision could construct a new well in the Camp Davis aquifer or purchase an existing well for supplemental supply. The study provided cost estimates for the supplemental well and for construction of a delivery pipeline from the new well to the district water supply system.

9.1.4.7 Star Valley

Sunrise Engineering (2009) investigated the feasibility of developing a regional water system in the Star Valley area. The study evaluated the water transmission and storage systems, water rights, and water quality from 19 existing public water systems in detail. Existing water systems in the valley are supplied by 24 wells and 16 springs sourced from the Madison Limestone, alluvial aquifers, the Salt Lake aquifer, and miscellaneous Paleozoic and Mesozoic aquifers. Sunrise Engineering (2009) suggested that the development of two regional water systems would be the most cost effective alternative.

9.1.4.8 Star Valley Ranch

Forsgren Associates (2008) conducted a Level II study for the Town of Star Valley Ranch. The study provides an evaluation of the existing water system, improvement alternatives, cost estimates, financing options, and permitting requirements. At the time of the study, Star Valley Ranch received its community water supply from two Paleozoic-sourced springs and two Salt Lake Formation wells. Forsgren Associates (2008) recommended that the town develop additional groundwater wells, update its water storage and delivery infrastructure, and install water meters.

9.1.5 Current WWDO and SEO projects

In addition to these recent studies, the WWDO is updating the previous Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) and constructing a hydrological model for surface flows in the basin. The U.S. Geological Survey (USGS) is currently conducting specific hydrogeologic investigations of Fish Creek near Wilson, Wyoming and the Snake River Alluvial Aquifer in the vicinity of the Jackson Hole Airport. Reports of these investigations can be obtained from the USGS publications website: http://pubs.er.usgs.gov/. Additionally, the USGS continues to collect real time streamflow data and periodic water quality at 16 USGS stream gaging stations located in the basin: http://waterdata.usgs.gov/wy/nwis/current/?type=flow.

9.1.6 Groundwater interference and interconnection with surface water

Other factors that must be considered for new groundwater projects 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. Wells alone do 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). Currently, this does not appear to be an issue of regional concern in the Snake/Salt River Basin.

9.2 Recommendations for future updates

The quality of the Wyoming State River Basin water plans is limited by the availability of data and the institutional resources used to develop the compiled information in a readily accessible format that is useful to stakeholders . While some information (e.g., hydrogeology studies, SEO groundwater permits, 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 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., SEO 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, UIC, waste and wastewater management), and for monitoring for potential impacts. 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 Snake/Salt River Basin 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. The recent formation of the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) should prove to be particularly valuable to a better understanding of groundwater resources in the Snake/Salt River Basin. 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/.

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**, 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 numerical modeling in selected areas that includes additional variables that affect infiltration and recharge (**section 5.1.3**).

Furthermore, there are several areas where additional geologic mapping would develop useful information for future Snake/Salt River Basin Water Plan updates. More detailed geologic mapping would better define the hydrogeologic role of the basin's geology, further identify areas where groundwater and surface water may be interconnected, and determine areas where vertical recharge may be enhanced by fracture permeability.

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Appendix A

Description of GIS Geologic Units, Snake/Salt River Basin, Wyoming, and Idaho

This appendix describes the 90 digital Geographic Information System (GIS) geologic units that comprise the Snake/Salt River Basin (SSRB) of Wyoming and Idaho. The stratigraphic descriptions in this appendix are for the units shown on Plate I. The 90 digital GIS geologic units are distributed as follows:

Wyoming 70 geologic units pages A-263 - 269
Idaho 20 geologic units pages A-263 - 269

These geologic units are compiled from the 1:500,000-scale digital state maps that cover the SSRB. 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. Rock-stratigraphic units that appear in the right-hand column of Plate 1 are in **boldface**.

SNAKE/SALT RIVER BASIN GEOLOGIC UNITS – WYOMING

There are 70 digital GIS geologic units in the Wyoming portion of the Snake/Salt River Basin (Love and Christiansen, 1985). The stratigraphic descriptions below are taken directly from Love and Christiansen (1985) with minor modifications. Unit labels for Idaho can be found at the end of the unit description for correlative units.

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Symbol Unit Description

CENOZOIC GEOLOGIC UNITS – WYOMING

Quaternary geologic units – Wyoming and Idaho

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 gravel.

Qg Glacial deposits (Holocene-Pleistocene) – Till and outwash of sand, gravel, and boulders.

Qls Landslide deposits (Holocene-Pleistocene) – Local intermixed landslide and glacial deposits, talus, and rock-glacier deposits.

Qb Basalt flows and intrusive igneous rocks (Holocene-Pleistocene) –Exposed in the Yellowstone area and in and adjacent to Absaroka Range of northwestern Wyoming. Idaho-**Qpub**

Qr Rhyolite flows, tuff, and intrusive igneous rocks (Holocene-Pleistocene) – Includes Plateau Rhyolite and interlayered sediments. Idaho-**Qpu3f**

Quaternary and Tertiary geologic units – Wyoming and Idaho

QTc Conglomerate (Pleistocene and (or) Pliocene) – Partly consolidated gravel above and flanking

some major streams.

Uncorrelated Idaho geologic units: Qpg- Glacial outwash, conglomerate, flood and terrace gravels

Tertiary geologic units – Wyoming and Idaho

Thr Huckleberry Ridge Tuff of Yellowstone Group (Pliocene) – Lavender to gray-brown welded rhyolite tuff.

Tii Intrusive and extrusive rocks (Pliocene and Miocene) – Igneous rocks, in composition from hornblende monzonite to basalt; in Yellowstone area includes andesite and basalt of Emerald Lake, rhyolite of Broad Creek, Pliocene Junction Butte Basalt, and gravel of Mount Evens.

Thl Heart Lake Conglomerate (Pliocene and Miocene) – Yellowish-gray, composed of moderately small fragments of volcanic rock, chiefly rhyolite and rounded pebbles and cobbles of limestone and quartzite.

Tsl Salt Lake Formation (Pliocene and Miocene) – White, gray, and green limy tuff, siltstone, sandstone, and conglomerate.

Tsi Shooting Iron Formation (Pliocene) – Greenish-gray to pink tuffaceous lacustrine claystone and siltstone, fine-grained sandstone, and conglomerate.

Tcc Conant Creek Tuff (Miocene) – Lavender rhyolite welded tuff.

Tte Teewinot Formation (Miocene) – White lacustrine clay, tuff, and limestone.

Tr Red conglomerate on top of Hoback and Wyoming Ranges (Miocene) – Locally derived clasts in a red clay and sand matrix.

Tcd Camp Davis Formation (Miocene) – Red conglomerate and red claystone, underlain by white tuff.

Tc Colter Formation (Miocene) – Dull-green gray tuff, volcanic conglomerate and sandstone.

Ti Intrusive igneous rocks (Miocene) – Felsic and mafic plutonic igneous bodies, the larger ones dominantly felsic.

Uncorrelated Idaho geologic units: Tpd- Stream and lake deposits.

Symbol Unit Description

Absaroka Volcanic Supergroup

Thorofare Creek Group

Twi Wiggins Formation (Eocene) – Light-gray volcanic conglomerate and white tuff, containing clasts of igneous rocks.

Ttl Two Ocean and Langford Formations (Eocene) – Dark-colored andesitic volcaniclastic rocks and flows underlain by light-colored andesitic tuffs and flows.

Tc Aycross Formation (Eocene) – Brightly variegated bentonitic claystone and tuffaceous sandstone, grading laterally into greenish-gray sandstone and claystone; in and east of Jackson Hole contains gold-bearing lenticular quartzite conglomerate.

Thorofare Creek and Sunlight Groups

Ttp Trout Peak Trachyandesite (Eocene) – Mixed clastic/volcanic and intermediate volcanic rocks.

Tts Wapiti Formation (Eocene) – Andesitic volcaniclastic rocks.

Thp Hominy Peak Formation (Eocene) – Mafic volcanic conglomerate and tuff.

Tv Volcanic conglomerate (Eocene) – Dark-brown to black conglomerate, poorly bedded, composed chiefly of basalt clasts in a basaltic tuff matrix.

Tcs Conglomerate of Sublette Range (Eocene) – Locally derived indurated angular conglomerate.

Twd Diamictite and sandstone (Eocene) – Diamictite grades laterally into other members of the formation.

Symbol *Unit Description*

Twdr Wind River Formation (Eocene) – Variegated red and white claystone and siltstone; largely non-tuffaceous except near the top.

Twlc La Barge and Chappo Members of the Wasatch Formation (Eocene) – Red, gray, and brown mudstone and conglomerate and yellow sandstone.

Tp Pass Peak Formation and equivalents (Eocene) – Quartzite conglomerate with sandstone and claystone.

Tdb Devils Basin Formation (Paleocene) – Light-gray sandstone, interbedded with green and gray claystone.

Th Hoback Formation (Paleocene and Upper Cretaceous) – Light-to-dark gray mudstone, siltstone, and sandstone, with a few beds of coal.

Tertiary and Cretaceous geologic units – Wyoming

TKp Hoback Formation (Paleocene and Upper Cretaceous) – Light-to-dark gray mudstone, siltstone, and sandstone, with a few beds of coal.

Cretaceous geologic units – Wyoming and Idaho

Kha Harebell Formation (Upper Cretaceous) – Gold-bearing quartzite conglomerate interbedded with olive-drab sandstone and green claystone.

Km Meeteetse Formation (Upper Cretaceous) – Light-colored, massive to thin-bedded sandstone, gray sandy shale, and coal beds.

Kmv Mesaverde Formation or Group (Upper Cretaceous) – Light-colored, massive to thin-bedded sandstone, gray sandy shale, and coal beds.

Kso Sohare Formation (Upper Cretaceous) – Lenticular gray brown sandstone and shale; coal-bearing in lower part. Gray to tan sandstone and thick coal beds; gold-bearing quartzite conglomerate in the lower part.

Ksb Sohare Formation and Bacon Ridge Sandstone (Upper Cretaceous) – Lenticular gray brown sandstone and shale; coal-bearing in lower part.

Kc Cody Shale (Upper Cretaceous) – Dull-gray shale, gray siltstone, and fine-grained sandstone.

Kbb Blind Bull Formation (Kbb) (Upper Cretaceous) – Gray to tan conglomeratic sandstone, siltstone, claystone, coal, and bentonite.

Kb Bacon Ridge Sandstone (Upper Cretaceous) – Gray to tan sandstone and thick coal beds; gold-bearing quartzite conglomerate in the lower part.

Kft Frontier Formation and Mowry and Thermopolis Shales (Upper Cretaceous)

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.

Kss Sage Junction, Quealy, Cokeville, Thom as Fork, and Smiths Formations (Lower Cretaceous)

Sage Junction Formation – Gray and tan siltstone and sandstone.

Quealy Formation – Variegated mudstone and tan sandstone.

Cokeville Formation – Tan sandstone, claystone, limestone, bentonite, and coal.

Thomas Fork Formation – Variegated mudstone and gray sandstone.

Smith Formation – Ferruginous black shale and tan to brown sandstone.

Symbol *Unit Description*

Ka Aspen Shale (Lower Cretaceous) – Light to dark-gray siliceous tuffaceous shale and siltstone, thin bentonite beds, and quartzitic sandstone.

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.

Kws Wayan and Smiths Formation (Lower Cretaceous) – Tan quartzite sandstone in upper part and black shale in lower part.

Kbr Bear River Formation (Lower Cretaceous) – Black shale, fine-grained brown sandstone, thin limestone, and bentonite beds.

Kg Gannett Group (Lower Cretaceous) – Red sandy mudstone, sandstone, and chert-pebble conglomerate; thin limestone and dark-gray shale in upper part, more conglomeratic in lower part. Includes Smoot Formation (red mudstone and siltstone), Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate. Upper Jurassic fossils have been reported from the Ephraim.

Uncorrelated Idaho geologic units: Ku- Upper Cretaceous thick detrital and fresh-water limestone beds. Kl-Lower Cretaceous shale, siltstone, red bed sandstone and fresh-water limestone.

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.

KJg Cloverly, Morrison, Sundance, and Gypsum 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.

Gypsum Formation – Interbedded red shale, dolomite, and gypsum.

Jurassic geologic units – Wyoming and Idaho

Jst Stump Formation, Preuss Sandstone or Redbeds, and Twin Creek Limestone (Upper and Middle Jurassic)

Stump Formation – Glauconitic siltstone, sandstone, and limestone.

Preuss Sandstone or Redbeds – Purple, maroon, and reddish-gray sandy siltstone and claystone; contains salt and gypsum in thick beds in some subsurface sections.

Twin Creek Limestone – Greenish-gray shaly limestone and limy siltstone. Includes Gypsum Spring Member. Idaho-Ju

Jsg Sundance and Gypsum Spring Formations (Jurassic)

Sundance Formation – Greenish-gray glauconitic sandstone and shale, underlain by red and gray nonglauconitic sandstone and shale.

Gypsum Spring Formation – Interbedded red shale, dolomite, and gypsum.

Symbol *Unit Description*

Jurassic and Triassic geologic units – Wyoming and Idaho

JTR Sundance and Gypsum Springs Formation and Nugget Sandstone (Jurassic and Triassic)

Sundance Formation – Greenish-gray glauconitic sandstone and shale, underlain by red and gray nonglauconitic sandstone and shale.

Gypsum Spring Formation – Interbedded red shale, dolomite, and gypsum.

Nugget Sandstone – Buff to pink crossbedded, well sorted quartz sandstone and quartzite.

JTRn Nugget Sandstone (Jurassic and Triassic) – Buff to pink crossbedded well-sized and well-sorted quartz sandstone and quartzite; locally has oil and copper-silver-zinc mineralization.

JTRnd Nugget Sandstone and Chugwater and Dinwoody Formations (Jurassic and Triassic)

Nugget Sandstone – Buff to pink crossbedded, well sorted quartz sandstone and quartzite.

Chugwater Formation – Composed of red siltstone and shale.

Dinwoody Formation – Olive-drab hard dolomitic thin-bedded siltstone and green shale.

Idaho-J

Triassic geologic units – Wyoming and Idaho

TRad Ankareh Formation, Thaynes Limestone, Woodside Shale, and Dinwoody Formation (Upper and Lower Triassic)

Ankareh Formation – Red and maroon shale and purple limestone.

Thaynes Limestone – Gray limestone and limy siltstone.

Woodside Shale – Red siltstone and shale.

Dinwoody Formation – Gray to olive-drab dolomitic siltstone.

TRcd 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.

Uncorrelated Idaho geologic units: TR- Sallow-marine to non-marine sediments, TRI- oxidized shale, siltstone, limestone, and conglomerate sandstone, and TRu- Limestone and chert above sandstone, siltstone and limestone.

Permian geologic units – Wyoming

Pp Phosphoria Formation (Permian) – Upper part is dark- to light-gray chert and shale with black shale and phosphorite at top; lower part is black shale, phosphorite, and cherty dolomite.

Idaho-**P**

Permian, Pennsylvanian, and Mississippian geologic units – Wyoming and Idaho

PIPMa Phosphoria, Wells, and Amsden Formations (Permian-Upper Pennsylvainian)

Phosphoria Formation (Permian) – Upper part is dark- to light-gray chert and shale with black shale and phosphorite at top; lower part is black shale, phosphorite, and cherty dolomite.

Wells Formation – Gray limestone interbedded with yellow limy sandstone.

Amsden Formation – Red and gray cherty limestone and shale, sandstone, and conglomerate.

Uncorrelated Idaho geologic unit: PPNc- Thrusted, marine detritus.

PIPM Wells and Amsden Formations (lower Permian-Upper Mississippian)

Wells Formation – Gray limestone inter bedded with yellow limy sandstone.

Amsden Formation – Red and gray cherty limestone and shale, sandstone, and conglomerate.

Symbol *Unit Description*

Pennsylvanian 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.

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 and Devonian geologic units – Wyoming and Idaho

MD Madison Group and Darby Formation (Upper Mississippian-Upper Devonian)

Madison Limestone or Group – Group includes Mission Canyon Limestone (blue-gray, massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty limestone and dolomite). Idaho-Ms

Darby Formation – Yellow and greenish-gray shale and dolomitic siltstone underlain by fetid brown dolomite.

Uncorrelated Idaho geologic unit– DSc- Deep-water argillite and quartzite.

Ordovician and Cambrian geologic units – Wyoming

O€ Bighorn Dolomite, Gallatin Limestone, and Gros Ventre Formation (Upper Ordovician-Middle Cambrian)

Bighorn Dolomite – Gray massive cliff-forming siliceous dolomite and locally dolomitic limestone.

Gallatin Limestone – Gray and tan limestone.

Gros Ventre Formation – Greenish-gray micaceous shale.

Precambrian geologic units – Wyoming

Wgn Granite gneiss (Precambrian – Late Archean) - Layered to massive, locally migmatitic; metasedimentary and metavolcanic rocks.

WVsv Metasedimentary and metavolcanic rocks (Precambrian – Late Archean)- 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.

Wmu Granitic rocks (Precambrian – Late Archean)- Granite

Ugn Oldest gneiss complex (Precambrian – Early Archean) - Area of migmatite related to emplacement of 2,600-Ma granite. These are the oldest rocks in Wyoming.

Appendix B

WWDC Groundwater Studies

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Wyoming River Basins				
Wyoming. Water Planning Program, 1973, Wyoming's groundwater supplies: Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, variously paged. WWC Engineering, Inc., 2007, in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., v. 1 and 2, variously paged.	All	Summary of available groundwater and groundwater sources.	Predictions of aquifer water quantity throughout the state of Wyoming.	Statewide river basin water planning process continues
Snake River Basin				
Sunrise Engineering, Inc., 2003, in association with Boyle Engineering, Inc., BBC Consulting, Inc., Hinckley Consulting, Fassett Consulting, Rendevous Engineering, and Nelson Engineering, Snake/Salt River Basin Plan, final report and technical memoranda: prepared for the Wyoming Water Development Commission, variously paged.	All	Develop basin plans with participation from local interest groups that provide defensible hydrologic data to quantify surface and ground water uses.	Current surface and ground water uses, water quality, future demand projects and future water use opportunities quantified and discussed. Continue with planning process with updates every five years.	Snake River Basin water planning process continues.
Afton				
Forsgren Associates, 1990, Afton municipal water supply Level II study, final report: prepared for the Wyoming Water Development Commission, variously paged. BRS, Inc., 1999, in association with Lidstone and Associates, Afton water supply project Level II, final report: prepared for the Wyoming Water Development Commission, variously paged.	Madison Limestone Amsden Formation	Assess the adequacy of the supply spring, and water facilities to meet Afton's water supply requirements. Analyses of water rights, infrastructure and economics. Provide conceptual design and cost estimates and environmental report.	Proposed PWS improvements are capable of serving Town of Afton by enhancing water collection and conveyance at Periodic Spring while providing reasonable protection of water facilities. Projects will entail significant funding.	
Sunrise Engineering, Inc., 2006, Siting, construction and testing of the Town of Afton new municipal East Alley Well: prepared for the Wyoming Water Development Commission, variously paged.	Alluvium	Level II status report to evaluate the hydrogeology of aquifer, determine depth to groundwater and aquifer thickness, complete and test new East Alley well, and assess groundwater quality.	East Alley well in alluvial formation was completed, developed and tested for aquifer hydraulics and water quality. Level III design and construction should proceed to connect well to PWS.	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Alpine				
Sunrise Engineering Inc., 1991, Alpine Junction water Level I study: prepared for the Wyoming Water Development Commission, variously paged.	Alluvial deposits Salt Lake Formation bedrock	Evaluate existing water supply, demands and facilities. Provide conceptual designs for regional water system, cost estimates and financing plans.	Proceed to Level II study. Drill and test a new test well, test several nearby wells and existing municipal wells. Prepare a revised cost estimate.	N/A
Rio Verde Engineering, 2001, Final report for the Alpine Spring irrigation supply project: prepared for the Wyoming Water Development Commission, variously paged.	Alluvial deposits	Evaluate Alpine spring for use in raw water irrigation system. Provide designs and cost estimates, economic analysis, environmental report, and analysis of state and federal permit requirements.	Project involves improvement of pond, spring area and irrigation distribution system. Project costs estimated at $773K.	N/A
Alpine (cont.)				
Rendezvous Engineering, PC, 2009, in association with Hinckley Engineering, Alpine master plan update Level II, final report: prepared for the Wyoming Water Development Commission, variously paged.	Mission Canyon and Lodgepole Limestones	Evaluate existing water supply, demands and facilities. Provide conceptual designs for regional water system, cost estimates and financing plans	Improve existing PWS by installing larger pumps and new control system in existing wells. Complete and test new well.	
Alta				
Rendezvous Engineering, PC, 2002, in association with Hinckley Engineering, Final report - Level I - Alta master plan: prepared for the Wyoming Water Development Commission, variously paged.	Glacial and alluvial deposits and rhyolite welded tuffs	Level I study to evaluate existing water supply and system facilities, water supply needs and alternatives for the Alta area.	Existing wells meet current demand. New wells can be drilled in present wellfield. Storage, control and transmission improvements and cost estimates provided.	
Rendezvous Engineering, PC, 2007, in association with Hinckley Engineering, Final report - Level II - Alta groundwater supply study: prepared for the Wyoming Water Development Commission, variously paged.		Evaluate hydrogeology and existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for supply and infrastructure additions and improvements.	Construct 2 new wells, upgrade existing well (TT#1), install new control building and replace transmission lines. Cost estimates and user fee analysis provided.	
Bedford				
Forsgren-Perkins Engineering, 1986, Bedford water supply study Level 1 final report: prepared for the Wyoming Water Development Commission, variously paged.	Paleozoic aquifer	Level I study to evaluate existing water supply and system facilities, water supply needs and alternatives for the Town of Bedford.	Improve water delivery system from Big Spring. Develop additional springs. Form a Water and Sewer District. Continue project to Level II.	
Forsgren-Perkins Engineering, 1987, Bedford water supply study Level II final report: prepared for the Wyoming Water Development Commission, variously paged.		Conduct water rights research, economic evaluations, water quality analyses and more detailed cost analyses of proposed improvements to existing system and alternatives.	Rebuild existing spring collection facility and develop supplemental spring. Install new well and construct new water transmission line. File for needed water rights.	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Buffalo Valley				
Jorgensen Engineering and Land Surveying PC, 1996 in association with Hinckley Engineering, Final – Buffalo Valley Level I – water supply project report: prepared for the Wyoming Water Development Commission, variously paged.	Burnt Ridge Moraine aquifer	Level I study to define existing water supply and system facilities, water supply needs and alternatives for Buffalo Fork Subdivision.	Recommend water district be formed, Level II study, minor upgrades to Well #2, replace current storage tank and installation of new transmission line.	
Jorgensen Engineering and Land Surveying PC, 1997 in association with Hinckley Engineering, Final report– Buffalo Valley water supply project Level II – Teton County: prepared for the Wyoming Water Development Commission, variously paged.		Site, drill and test exploratory well. Analyze alternatives and permit requirements for water storage on National Forest Land.	Exploration well completed and pump tested. Production and water quality acceptable. Recommend new storage tank and supply line. Cost estimates and user fee analysis provided.	
Etna				
Forsgren Associates, 1993, in association with Weston Engineering, Etna Water and Sewer District water supply system – part of the Star Valley Level II study, final report (revised): prepared for the Wyoming Water Development Commission, variously paged.	Paleozoic aquifer and Salt Lake aquifers	Evaluate existing water supply, demands and facilities. Provide conceptual designs for regional water system, cost estimates and financing plans. Construct and test new well.	Improve existing spring collection facilities. New groundwater well installed and tested. Make water storage and transmission line improvements.	
Fairview				
Forsgren Associates, 1991, Star Valley municipal water supply Level II Study- report of the Fairview water supply system, final report: prepared for the Wyoming Water Development Commission, variously paged.	Tertiary aquifer	Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions.	Rehabilitate existing supply spring. Drill supplemental well. Transmission/ distribution system requires improvements with cost estimates provided.	
Freedom				
Forsgren Associates, 1992, Freedom Water and Sewer District water supply system – part of the Star Valley Level II study, final report (revised): prepared for the Wyoming Water Development Commission, variously paged.	Salt Lake aquifer	Evaluate existing water supply, demands and facilities. Provide conceptual designs for regional water system, cost estimates and financing plans. Design new well (see TriHydro report, below).	New well completed and tested. Improve existing water transmission and delivery infrastructure; cost estimates provided.	
TriHydro Corporation, 1993, Construction and testing report Freedom No. 2 test well, Freedom, Wyoming: prepared for the Wyoming Water Development Commission, variously paged.		Install Freedom No. 2 test well. Determine aquifer characteristics, evaluate water quality and conduct aquifer testing to determine feasibility of converting test well to a production well.	Completed test well met project production and water quality objectives. Move to Level III conversion to production well.	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Grover				
Forsgren Associates, 1991, Star Valley municipal water supply Level II Study- report of the Grover water supply system, final report: prepared for the Wyoming Water Development Commission, variously paged.	Salt Lake aquifer	Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions.	Retain 1 supply spring, abandon 2 others. Construct and test new well. Improve existing water transmission and delivery infrastructure; cost estimates provided.	
Hoback Junction				
Forsgren Associates, 1991, Star Valley municipal water supply Level II Study- report of the Grover water supply system, final report: prepared for the Wyoming Water Development Commission, variously paged.	Paleozoic through Quaternary GW prospects evaluated	Level I study to identify water source with sufficient quantity and quality to meet domestic and fire protection demands at affordable cost. Identify water storage alternatives for Hoback Junction.	Recommend water district be formed and service area defined, project move to Level II study to fund completion of test well.	
Jackson				
Nelson Engineering, 1984, Jackson water feasibility study, groundwater exploration program: prepared for the Wyoming Water Development Commission, variously paged.	Alluvial aquifer	Level I study to define existing water supply and system facilities, water supply needs and alternatives. Identify water source with sufficient quantity and quality to meet current and future demands.	Potential groundwater prospects identified and designed exploratory drilling program recommended.	
Nelson Engineering, 1993, Town of Jackson groundwater exploration program, final report: final report: prepared for the Wyoming Water Development Commission, variously paged.		Project to locate and evaluate feasibility of developing groundwater supply source for Jackson. Evaluate and price permits required and treatment, transmission, control, and storage infrastructure needs.	Two exploration wells were drilled and tested. Manganese and iron levels were too high to treat economically in well #1 but water quality was acceptable in well #2. A water development plan was designed and cost estimates included.	
Kennington Springs				
Keller Associates, Inc., 2003, Kennington Springs Pipeline Company Level I water system reconnaissance study, final report: prepared for the Wyoming Water Development Commission, variously paged.	Twin Creek aquifer	Provide comprehensive evaluation of the existing water system and make recommendations to meet requirements imposed by future growth in the area	Spring supplies adequate amounts of good quality water to residents. Transmission and distribution systems are in good condition. System improvements proposed along with cost estimates	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
North Alpine				
Rendezvous Engineering, PC, 2009, in association with Hinckley Consulting, Final report, Level II North Alpine water supply study: prepared for the Wyoming Water Development Commission, variously paged	Salt Lake aquifer	Level II study, evaluation of existing water system, improvement alternatives and cost estimates, financing options and permitting requirements.	Salt Lake aquifer wells provide adequate supplies of good quality water. Two new wells can be sited in present wellfield. Transmission/distribution system requires improvements with cost estimates provided.	N/A
Osmond				
Forsgren Associates, 1991, Star Valley municipal water supply Level II Study- report of the Osmond water supply system, final report: prepared for the Wyoming Water Development Commission, variously paged.	Mesozoic aquifer	Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions.	Redevelop existing supply spring. Consider future supplemental well. Transmission/distribution system requires improvements with cost estimates provided.	
Rafter J				
Jorgensen Engineering and Land Surveying PC, 1998 in association with Gordon-Prill-Drapes and Hinckley Engineering, Final – Rafter J water supply Level II study: prepared for the Wyoming Water Development Commission, variously paged.		Evaluate hydrogeology and existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for supply and infrastructure additions and improvements.	Construct new well, well house with standby generator and transmission line. Make minor upgrades to existing storage tank.	
Smoot				
Forsgren Associates, 1991, Star Valley municipal water supply Level II Study- report of the Smoot water supply system, final report: prepared for the Wyoming Water Development Commission, variously paged.	Mesozoic aquifer	Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions.	Redevelop existing supply springs. Drill supplemental well. Transmission/ distribution system requires improvements with cost estimates provided.	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Squaw Creek				
AVI Professional Corporation, 1991, in association with Lidstone and Anderson, Inc., Level I study - Squaw Creek water supply project: prepared for the Wyoming Water Development Commission, variously paged.	Camp Davis, Cloverly Formations and Twin Creek Limestone	Level I study to define existing water supply and system facilities, water supply needs and alternatives. Identify water source with sufficient quantity and quality to meet current and future demands.	Investigate redevelopment of existing spring and development potential of other springs. Drill and test deep well. Revise plans and cost estimates pending results from well and spring tests.	
Lidstone and Anderson, Inc., 1994, in association with AVI Professional Corporation, Squaw Creek water supply project – Level II: prepared for the Wyoming Water Development Commission, variously paged.	Alluvial aquifer	Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions. Two test wells drilled.	Two test wells drilled and pump tested, production and water quality are adequate. Transmission, storage and treatment systems require additions and upgrades with cost estimates provided.	
AVI Professional Corporation, 2012, in association with Dahlgren Consulting, Pierson Land Works, Stockdale Consulting, Squaw Creek water supply Level II study: prepared for the Wyoming Water Development Commission, variously paged.	Camp Davis and Nugget Formations	Level II study to explore feasibility of acquiring additional source supply. Evaluate system upgrades and fire protection.	Construct a test well or acquire existing well for supplemental supply. Construct a pipeline from new well to district system. Cost estimates provided.	
Star Valley Ranch				
Forsgren Associates, 1990, in association with Weston Engineering, Star Valley Ranch master plan: prepared for the Wyoming Water Development Commission, variously paged.	Paleozoic aquifer including Gallatin Limestone	Evaluation of existing water system, improvement alternatives and cost estimates, financing options and permitting requirements.	Further groundwater development is required to provide adequate and secure supply. Storage, transmission and distribution systems require additions and improvements with cost estimates provided.	

Appendix B. cont.

Citation(s)	Aquifer/ Formation	Project Description	Results/Recommendations	Current Status
Star Valley				
Forsgren Associates, 1989, Star Valley municipal water supply, Level I study: prepared for the Wyoming Water Development Commission, variously paged.	Paleozoic, Salt Lake	Level I study of six community water systems in Star Valley: Etna, Freedom, Grover, Fairview, Osmond and Smoot. Provide comprehensive evaluation of existing water systems.	Redevelop 8 of 9 supply springs, replace or renovate existing wells. Upgrade existing transmission and distribution systems. See Level II reports for named individual communities in this appendix.	Moving forward with drilling and testing of production scale wells.
Sunrise Engineering, Inc., 2009, Star Valley Regional Master Plan - Town of Afton – water system investigation and evaluation: prepared for the Wyoming Water Development Commission, variously paged.	Madison Limestone, Alluvium, Salt Lake, miscellaneous Paleozoic and Mesozoic aquifers	Evaluate water system, water rights, transmission and storage systems, water quality in Star Valley area.	Existing supplies from 24 wells and 16 springs with good water quality. Suggest development of regional system with cost estimates provided.	
Star Valley (cont.)				
Sunrise Engineering, Inc., 2009, Star Valley Regional Master Plan – North Alpine Service and Improvement District – water system investigation and evaluation: prepared for the Wyoming Water Development Commission, variously paged.	Madison Limestone, Alluvium, Salt Lake, miscellaneous Paleozoic and Mesozoic aquifers	Evaluate water system, water rights, transmission and storage systems, water quality in Star Valley area.	Existing supplies from 24 wells and 16 springs with good water quality. Suggest development of regional system with cost estimates provided.	
Sunrise Engineering, Inc., 2009, in association with Boyle Engineering, Harvey Economics, Rendezvous Engineering and Collins Planning Associates, Star Valley Regional Master Plan final report: prepared for the Wyoming Water Development Commission, variously paged.	Madison Limestone, Alluvium, Salt Lake, miscellaneous Paleozoic and Mesozoic aquifers	Evaluate water system, water rights, transmission and storage systems, water quality in Star Valley area.	Existing supplies from 24 wells and 16 springs with good water quality. Suggest development of regional system with cost estimates provided.	
Thayne				
Forsgren Associates, 1995, Thayne area water supply, Level I study: prepared for the Wyoming Water Development Commission, variously paged.	Salt Lake Formation	Evaluation of existing water system, improvement alternatives and cost estimates, financing options and permitting requirements.	Redevelop Flat Creek Springs. Construct supplemental groundwater well. Tie into Bedford system. Upgrade existing transmission and distribution systems.	N/A
Forsgren Associates, 1997, Thayne water supply, Level II study: prepared for the Wyoming Water Development Commission, variously paged.		Level II study to evaluate existing water supply, demands and facilities. Provide conceptual designs, cost estimates and financing plans for improvements and additions.	Redevelop Flat Creek Springs. Supplemental well was constructed and tested. Install meters. Upgrade existing transmission and distribution systems with cost estimates provided.	

Appendix C

GIS Dataset Sources for Figures and Plates

Dataset	Presented in	Source
GEOLOGY		
Snake/Salt River Basin geology	Plate I, various figures	Modified from Vuke, Porter, et al., 2007 Love, J.D., Christiansen, A.C., 1985
Precambrian basement structure contour	Plate I	Modified from Blackstone, 1993
Precambrian basement faults	Plate I	Modified from Blackstone, 1993
cross-section lines	Plate I	WSGS
Lineaments	Plate I	Cooley, M. E., 1986
faults, Wyoming	Plate I, Plate II	Vuke, Porter, et al., 2007 Love, J.D., Christiansen, A.C., 1985
faults, Idaho	Plate I, Plate II	Love and Christiansen 1985, and Stoeser et al. 2005
Hydrogeology (includes aquifer outcrop areas)	Plate II, Figures 6-1, 6-2, 6-3, 6-4, 6-5, 6-6	T. Bartos, USGS, 2013
GROUNDWATER		
Aquifer recharge as a percent of precipitation	Figure 6-7	Modified from Hamerlinck and Arneson, 1998, and Daly and Taylor, 1998
Aquifer sensitivity	Figure 5-3	Hamerlinck and Arneson, 1998
Average annual precipitation, 1981-2010	Figure 3-3	PRISM Climate Group, Oregon State University
Environmental water sample locations		USGS, Environmental water sample locations GIS dataset of 2010
Estimated net annual aquifer recharge	Figure 5-2	Hamerlinck and Arneson, 1998
Produced water sample locations		WOGCC, Produced water database, 2009
Springs		Stafford and Gracias, WSGS, 2009
SWAP locations	Figure 5-11	Modified from Trihydro Corporation, 2004
WWDC potential groundwater development areas		Digitized from BRS, Inc., 2003e
Permitted wells	Figures 8-1, 8-2, 8-3, 8-4, 8-5, 8-6, 8-7	Wyoming State Engineer's Office, 2012 Idaho Department of Water Resources, 2012
POTENTIAL GROUNDWATER CONTAMINANTS		
Abandoned mine sites	Figure 5-7	Created from WDEQ Abandoned Mine Land table of 2010
Active coal mine	Figure 5-8	WDEQ, Land Quality Division, 2012
Active disposal and injection wells	Figure 5-4	Modified from WOGCC well header data as of 2009
Small, Limited, and Regular Mining Permits	Figure 5-8	WDEQ LQD, 2012
Non Coal Mines	Figure 5-8	WDEQ LQD, 2011
Storage tanks	Figure 5-10	Modified from WDEQ Solid and Hazardous Waste Division (SHWD) storage tank table of 2009
Active Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Figure 5-6	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2009
Commercial oil and gas disposal pits	Figure 5-6	WDEQ/WQD commercial oil and gas disposal pit GIS dataset of 2012

Appendix C. cont.

Dataset	Presented in	Source
Pollution Control Facilities	Figure 5-6	WDEQ/WQD Groundwater Program known contaminated areas GIS dataset of 2012
Oil and gas fields	Figure 5-4	De Bruin, 2007
Pipelines	Figure 5-4	Wyoming Pipeline Authority
Solid and hazardous waste facilities	Figure 5-10	Modified from WDEQ SHWD solid and hazardous waste facilities table of 2009
Underground Injection Control (UIC) Class I and V wells	Figure 5-5	Modified from WDEQ/WQD UIC GIS dataset of 2009
Voluntary Remediation Program (VRP) sites	Figure 5-10	Modified from WDEQ SHWD VRP tables and GIS datasets of 2009
WSGS mines, pits, mills, and plants	Figure 5-9	Harris, 2004
BASE DATA		
Basin boundary	Plate I, various figures	Modified from USGS National Hydrography Dataset hydrologic units
Elevation	Plate I, various figures	Modified from U.S. Geological Survey, 1999
Hillshade	Plate I, various figures	USGS, 1999
Lakes	Plate I, various figures	USGS, National Hydrologic Dataset
Rivers	Plate I, various figures	USGS, National Hydrologic Dataset
Wyoming state boundary	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho state boundary	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming counties	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho counties	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming townships	Plate I, various figures	Premier Data Services, 2008
Idaho townships	Plate I, various figures	Bureau of Land Management
Mountain peaks	Physiographic features figure	WSGS, unpublished mountain peaks GIS dataset of 2008
Wyoming roads	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho roads	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
SSB Towns	Plate I, various figures	NAUS, 2003
Yellowstone Boundary	various figures	Spatial Analysis Center, Yellowstone National Park, 1995

Appendix D

Snake River Compact

SNAKE RIVER COMPACT, 1949

The States of Idaho and Wyoming, parties' signatory to this Compact, have resolved to conclude a compact as authorized by the Act of June 3, 1948 (62 Stat. 294), and after negotiations participated in by the following named State commissioners:

For Idaho:

Mark R. Kulp, Boise
N. V. Sharp, Filer
Charles H. Welteroth, Jerome
Roy Marquess, Paul
Ival V. Goslin, Aberdeen
R. Willis Walker, Rexburg
Alex O. Coleman, St. Anthony
Leonard E. Graham, Rigby
Charles E. Anderson, Idaho Falls
A. K. Van Orden, Blackfoot

For Wyoming:

L. C. Bishop, Cheyenne
E. B. Hitchcock, Rock Springs
J. G. Imeson, Jackson
David P. Miller, Rock Springs
Carl Robinson, Afton
Ciril D. Cranney, Afton
Clifford P. Hansen, Jackson
Clifford S. Wilson, Driggs, Idaho
Lloyd Van Deburg, Jackson

and by R. J. Newell, representative of the United States of America, have agreed upon the following articles, to-wit:

ARTICLE I

A. The major purposes of this compact are to provide for the most efficient use of waters of the Snake River for multiple purposes; to provide for equitable division of such waters; to remove causes of present and future controversies; to promote interstate comity; to recognize that the most efficient utilization of such waters is required for the development of the drainage area of the Snake River and its tributaries in Wyoming and Idaho; and to promote joint action by the states and the United States in the development and use of such waters and the control of floods.

B. Either State using, claiming or in any manner asserting any right to the use of the waters of the Snake River under the authority of either State shall be subject to the terms of this Compact.

ARTICLE II

As used in this Compact:

A. The term "Snake River" as distinguished from terms such as "Snake River and its tributaries" shall mean the Snake River from its headwaters to the Wyoming-Idaho boundary and all tributaries flowing into it within the boundaries of Wyoming, and the Salt River and all its tributaries

B. The terms "Idaho" and "Wyoming" shall mean, respectively, the State of Idaho and the State of Wyoming, and, except as otherwise expressly provided, either of those terms or the term "State" or "States" used in relation to any right or obligation created or recognized by this Compact shall include any person or entity of any nature whatsoever, including the United States;

C. The term "domestic use" shall mean the use of water by an individual, or by a family unit or household for drinking, cooking, laundering, sanitation and other personal comforts and necessities; and for the irrigation of a family garden or orchard not exceeding one-half acre in area;

D. The term "stock water use" shall mean the use of water for livestock and poultry

E. The term "established Wyoming rights" shall mean Snake River water rights that have been validly established of record in Wyoming prior to July 1, 1949, for use in Wyoming.

ARTICLE III

A. The waters of the Snake River, exclusive of established Wyoming rights and other uses coming within the provisions of (c) of this Article III, are hereby allocated to each State for storage or direct diversion as follows:

To Idaho ...……..... 96 percent

To Wyoming …..... 4 percent

subject to the following stipulations and conditions as to the four percent allocated to Wyoming:

1. One-half may be used in Wyoming by direct diversion or by storage and subsequent diversion without provision being made for replacement storage space;

2. The other one-half may be diverted for direct use or stored for later diversion and use on the condition that there shall have been provided for reimbursement of Idaho users replacement storage space to the extent of one-third of the maximum annual diversion in acre-feet but not in excess, however, of one-third of half the total hereby allocated to Wyoming. Until this total replacement storage space has been made available, provision for meeting its proportionate part of this total shall be a prerequisite to the right to use water in Wyoming for any irrigation project authorized after June 30, 1949, for construction by any federal agency.

B. The amount of water subject to allocation as provided in (a) of this Article III shall be determined on an annual water-year basis measured from October 1 of any year through September 30 of the succeeding year. The quantity of water to which the percentage factors in (a) of this Article III shall be applied through a given date in any water year shall be, in acre-feet, equal to the algebraic sum of:

1. The quantity of water, in acre-feet, that has passed the Wyoming state line in the Snake River to the given date, determined on the basis of gaging stations to be established at such points as are agreed on under the provisions of (b) of Article VI;

2. The change during that water year to the given date in quantity of water, in acre-feet, in any existing or future reservoirs in Wyoming which water is for use in Idaho;

3. The quantity of water, in acre-feet, stored in that water year and in storage on the given date for later diversion and use in Wyoming, under rights having a priority later than June 30, 1949;

4. One-third of the quantity of water, in acre-feet, excluding any storage water held over from prior years, diverted, under rights having a priority later than June 30, 1949, in that water year to the given date:

(a) From the Snake River for use that year on lands in Wyoming; and

(b) From tributaries of the Salt River for use that year on lands in Idaho.

C. There are hereby excluded from the allocations made by this Compact:

1. Existing and future domestic and stock water uses of water; provided, that the capacity of any reservoir for stock water shall not exceed twenty (20) acre-feet;

2. Established Wyoming rights; and

3. All water rights for use in Idaho on any tributary of the Salt River heading in Idaho, which were validly established under the laws of Idaho prior to July 1, 1949; and all such uses and rights are hereby recognized.

ARTICLE IV

No water of the Snake River shall be diverted in Wyoming for use outside the drainage area of the Snake River except with the approval of Idaho; and no water of any tributary of the Salt River heading in Idaho shall be diverted in Idaho for use outside the drainage area of said tributary except with the approval of Wyoming.

ARTICLE V

Subject to the provisions of this Compact, waters of the Snake River may be impounded and used for the generation of electrical power, but such impounding and use shall be subservient to the use of such waters for domestic, stock and irrigation purposes, and shall not interfere with or prevent their use for such preferred purposes. Water impounded or diverted in Wyoming exclusively for the generation of electrical power shall not be charged to the allocation set forth in Article III of this Compact.

ARTICLE VI

A. It shall be the duty of the two States to administer this Compact through the official in each State who is now or may hereafter be charged with the administration of the public water supplies, and to collect and correlate through such officials the data necessary for the proper administration of the provisions of this Compact. Such officials may, by unanimous action, adopt rules and regulations consistent with the provisions of this Compact.

B. The States shall in conjunction with other responsible agencies cause to be established, maintained and operated such suitable water gaging stations as they find necessary to administer this Compact. The United States Geological Survey, or whatever federal agency may succeed to the functions and duties of that agency, so far as this Compact is concerned, shall collaborate with officials of the States charged with the administration of this Compact in the execution of the duty of such officials in the collection, correlation and publication of information necessary for its proper administration.

C. In the case of failure of the administrative officials of the two States to agree on any matter necessary to the administration of this Compact, the Director of the United States Geological Survey, or whatever official succeeds to his duties, shall be asked to appoint a federal representative to participate as to the matters in disagreement, and points of disagreement shall be decided by majority vote.

ARTICLE VII

A. Either State shall have the right to file applications for and receive permits to construct or participate in the construction and use of any dam, storage reservoir or diversion works in the other State for the purpose of conserving and regulating its allocated water and to perfect rights thereto. Either State exercising this right shall comply with the laws of the other State except as to any general requirement for legislative approval that may be applicable to the granting of rights by one State for the diversion or storage of water for use outside of that State.

B. Each claim or right hereafter initiated for storage or diversion of water in one State for use in the other State shall be filed in the office of the proper official of the State in which the water is to be stored or diverted, and a duplicate copy of the application, including a map showing the character and location of the proposed facilities and the lands to be irrigated, shall be filed in the office of the proper official of the State in which the water is to be used. If a portion or all the lands proposed to be reclaimed are located in a State other than the one in which the water is to be stored or diverted, then, before approval, said application shall be checked against the records of the office of the State in which the water is to be used, and a notation shall be placed thereon by the officer in charge of such records as to whether or not he approves the application. All endorsements shall be placed on both the original and duplicate

copies of all such applications and maps filed to the end that the records in both States may be complete and identical.

ARTICLE VIII

A. Neither State shall deny the right of the United States, and, subject to the conditions hereinafter contained, neither State shall deny the right of the other State to acquire rights to the use of

water, or to construct or participate in the construction and use of diversion works and storage reservoirs with appurtenant works, canals and conduits in one State for the purpose of diverting, conveying, storing or regulating water in one State for use in the other State, when such use is within the allocation to such State made by this Compact.

B. Either State shall have the right to acquire such property rights as are necessary to the use of water in conformity with this Compact in the other State by donation, purchase or through the exercise of the power of eminent domain. Either State, upon the written request of the Governor of the other State, for the benefit of whose water users' property is to be acquired in the State to which such written request is made, shall proceed expeditiously to acquire the desired property either by purchase at a price satisfactory to the requesting State, or, if such purchase cannot be made, then through the exercise of its power of eminent domain and shall convey such property to the requesting State or such entity as may be designated by the requesting State; provided, that all costs of acquisition and expenses of every kind and nature whatsoever incurred in obtaining the requested property shall be paid by the requesting State at the time and in the manner prescribed by the State requested to acquire the property.

C. Should any facility be constructed in either State by and for the benefit of the other State, as above provided, the construction, repair, replacement, maintenance and operation of such facility shall be subject to the laws of the State in which the facility is located, except that, in the case of a reservoir constructed in either State for the benefit of the other State, the proper officials of the State in which the facility is located shall permit the storage and release of any water to which the other State is entitled under this Compact.

D. Either State having property rights in the other State acquired as provided in B of this Article VIII shall pay to the political subdivisions of the State in which such property rights are located, each and every year during which such rights are held, a sum of money equivalent to the average annual amount of taxes assessed against those rights during the ten years preceding the acquisition of such rights in reimbursement for the loss of taxes to said political subdivision of the State, except that this provision shall not be applicable to interests in property rights the legal title to which is in the United States. Payments so made to a political subdivision shall be in lieu of any and all taxes by that subdivision on the property rights for which the payments are made.

ARTICLE IX

The provisions of this Compact shall not apply to or interfere with the right or power of either State to regulate within its boundaries the appropriation, use and control of waters allocated to such State by this compact.

ARTICLE X

The failure of either State to use the waters, or any part thereof, the use of which is allocated to it under the terms of this Compact, shall not constitute a relinquishment of the right to such use to the other State, nor shall it constitute a forfeiture or abandonment of the right to such use.

ARTICLE XI

In case any reservoir is constructed in one State where the water is to be used principally in the other State, sufficient water not to exceed five (5) cubic feet per second shall be released at all times, if necessary for stock water use and conservation of fish and wildlife.

ARTICLE XII

The provisions of this Compact shall remain in full force and effect unless amended or terminated by action of the legislatures of both States and consented to and approved by the Congress of the United States in the same manner as this Compact is required to be ratified and approved to become effective; provided, that in the event of such amendment or termination all rights theretofore established hereunder or recognized hereby shall continue to be recognized as valid by both States notwithstanding such amendment or termination.

ARTICLE XIII

Nothing in this Compact shall be construed to limit or prevent either State from instituting or maintaining any action or proceeding, legal or equitable, for the protection of any right under this Compact or the enforcement of any of its provisions.

ARTICLE XIV

A. Nothing in this Compact shall be deemed:

1. To affect adversely any rights to the use of the waters of the Snake River, including its tributaries entering downstream from the Wyoming-Idaho state line, owned by or for Indians, Indian tribes and their reservations. The water required to satisfy these rights shall be charged against the allocation made to the State in which the Indians and their lands are located;

2. To impair or affect any rights or powers of the United States, its agencies or instrumentalities, in and to the use of the waters of the Snake River nor its capacity to acquire rights in and to the use of said waters;

3. To apply to any waters within the Yellowstone National Park or Grand Teton National Park;

4. To subject any property of the United States, its agencies or instrumentalities to taxation by either State or subdivisions thereof, nor to create an obligation on the part of the United States, its agents or instrumentalities, by reason of the acquisition, construction or operation of any property or works of whatsoever kind, to make any payments to any State or political

subdivisions thereof, state agency, municipality or entity whatsoever in reimbursement for the loss of taxes;

5. To subject any works of the United States used in connection with the control or use of waters, which are the subject of this, Compact to the laws of any State to an extent other than the extent to which these laws would apply without regard to this Compact.

B. Notwithstanding the provisions of A of this Article, any beneficial uses hereafter made by the United States, or those acting by or under its authority, within either State, of the waters allocated by this Compact shall be within the allocations hereinabove made for use in that State and shall be taken into account in determining the extent of use within that State.

ARTICLE XV

This Compact shall become operative when approved by legislative enactment by each of the States, and when consented to by the Congress of the United States.

ARTICLE XVI

Wyoming hereby relinquishes the right to the allocation of stored water in Grassy Lake Reservoir, as set forth in Wyoming's reservoir Permit No. 4631 Res. and evidenced by Certificate No. R-1, page 318, and all claims predicated thereon.

IN WITNESS WHEREOF the Commissioners have signed this compact in quadruplicate, one (1) of which shall be filed in the archives of the Department of State of the United States of America and shall be deemed the authoritative original, and of which a duly certified copy shall be forwarded to the Governor of each of the States.

Done at the city of Cheyenne, in the state of Wyoming, this 10th day of October, in the year of our Lord, one thousand nine hundred and forty-nine.

Commissioners for Idaho	Commissioners for Wyoming
MARK R. KULP	L. C. BISHOP
N. V. SHARP	E. B. HITCHCOCK
CHARLES H. WELTEROTH	J. G. IMESON
ROY MARQUESS	DAVID P. MILLER
IVAL V. GOSLIN	CARL ROBINSON
R. WILLIS WALKER	CIRIL D. CRANNEY
ALEX O. COLEMAN	CLIFFORD P. HANSEN
LEONARD E. GRAHAM	CLIFFORD W. WILSON
CHARLES E. ANDERSON	LLOYD VAN DEBURG
A. K. VAN ORDEN	

I have participated in the negotiation of this Compact and intend to report favorably thereon to the Congress of the United States.

R. J. NEWELL

Representative of the United States of America

NOTES

Congressional Consent to Negotiations. --- By the Act of June 3, 1948 (62 Stat. 294), the Congress gave its consent to the negotiation of a Snake River Compact by the States of Idaho and Wyoming. The consent was given “upon condition that one suitable person, who shall be appointed by the President of the United States, shall participate in said negotiations as the representative of the United States and shall make report to the Congress of the proceedings and of any compact entered into.” The Act also provided than any compact agreed upon shall not be effective until ratified by the Legislatures of the States and “approved” by the Congress and that “nothing in this Act shall apply to any waters within the Yellowstone National Park and Grand Teton National Park or shall establish any right or interest in or to any lands within the boundaries thereof or in subsequent additions thereto.”

Congressional Consent to and Legislative History of the Compact. --- The “consent and approval" of the Congress was given the Snake River Compact by the Act of March 21, 1950 (64 Stat. 29), from which the text of the Compact above is taken. Section 2 of this Act "expressly reserved" the "right to alter, amend, or repeal this Act."

For legislative history, see S. 3159, 8lst Congress; House Report 1743 (Committee on Public Lands), 8lst Congress; 96 Cong. Rec. 2573-2575, 3063-3065 (1950); P.L. 464, 8lst Congress.

Presidential and Budget Bureau Comments on Compact. --- In connection with the negotiations of the Yellowstone River Compact, the President expressed his views on certain provisions of the Snake River Compact in a letter to the Federal Representative dated May 3, 1950, to which was attached to a memorandum from the Director of the Bureau of the Budget dated April 21, 1950. The two documents read as follows:

May 3, 1950

"MY DEAR MR. NEWELL: The purpose of this letter is to call your attention to a problem of growing concern and, in the solution of which, the Federal Representatives assigned to interstate water compact commissions are in a position to perform a valuable public service. I refer to the somewhat recent tendency to incorporate in interstate water compacts questionable or conflicting provisions imposing restrictions on use of waters by the United States, such as appear in the Snake River Compact enactment, which I approved on March 21, 1950 (Public Law 464, 8lst Congress, 2nd Session).

"In this particular case, the possibility of misinterpretation of certain apparently conflicting provisions was not considered to be serious enough to warrant withholding approval of the enrolled enactment of the Congress (S. 3159). Such provisions however, if followed as precedent for general application, may jeopardize the prospect of consent and approval of compacts by the Federal Government because of the far reaching effects such provisions might have upon the interests of the United States. This matter is further discussed in a memorandum to me from the Director of the Bureau of the Budget, a copy of which is enclosed for your information and guidance.

"I fully realize how difficult it is to resolve the numerous complexes jurisdictional and other problems encountered in reaching agreement upon the allocation of waters of an interstate stream. At the same time, I am impressed with the importance of insuring that compact provisions reflect as clearly

as possible a recognition of the respective responsibilities and prerogatives of the United States and the affected States. I can assure you that any efforts made by you and the other compact commissioners with whom you have occasion to collaborate in eliminating or correcting this area of possible conflict, will be appreciated.

"Sincerely yours,

"Harry S. Truman"

"April 21, 1950

"Memorandum for the President:

"Analysis of the enrolled enactment granting the consent and approval of the Congress to the Snake River Compact, prior to your approval on March 21,1950, (Public Law 464, 8lst Congress, 2nd Session), revealed the possibility of misinterpretation of certain apparently conflicting provisions, which did not appear to be serious enough in this particular case to provide a sound basis for recommending disapproval of the bill, but which, if followed as precedent for general application, might have far reaching effects upon the interests of the United States. The conflicts arise primarily between specific provisions imposing restrictions upon uses of water by the United States for power and other purposes, and the general savings clause in Article XIV. This article provides that nothing in the Compact shall be deemed to impair or affect any rights or powers of the United States in and to the use of the waters of the

Snake River nor its capacity to acquire rights in and to the use of said waters. By reason of such conflicts, doubts may rise as to the extent of the control which the States concerned may exercise over the rights, interests and structures owned or built by the United States on the river. The resulting possibility of confusion thus tends to defeat one of the basic purposes of the Compact, of settling the respective rights and interests of the Federal and State Governments in, over and to the river.

"The Committee on Public Lands of the House of Representatives, in its report on the bill (S. 3159) recorded its interpretation of the term "beneficial uses" appearing in Article XIV-B, as not regarded by the Committee as including the use and control of water by the United States by reason of its power with respect to navigable waters under the commerce clause of the Constitution (H. R. Report No. 1743, 8lst Congress, 2nd Session). It is also significant that the Congress saw fit to include in the enactment a provision (Section 2) expressly preserving to the United States the right to alter, amend, and repeal the Act at any time.

"Somewhat similar provisions appear in the proposed Cheyenne River Compact now pending before Congress (H. R. 3336 and S. 1211) and in the Republican River Compact approved May 26, 1943, and the Belle Fourche River Basin Compact approved February 26, 1944. In approving each of these latter enactments, President Roosevelt issued a statement emphasizing that the procedure prescribed by the bill for exercise of the powers of the Federal Government, would not be entirely satisfactory in all circumstances and that these Compacts should not serve as precedents, particularly for streams where there appears to be a possible need for Federal comprehensive multiple purpose development or where opportunities for important electric power projects are present. Likewise, the Snake River Compact should not serve as a precedent.

"In its report in S. 3159 the Public Lands Committee of the Senate expressed the view that he compact method is the logical and proper manner to settle interstate water controversies. With this view, I am in accord but I am also mindful that Compact provisions, which are subject to misinterpretation or leave in doubt the respective rights and interests of the United States and the affected States, serve to impair these rights. It is obvious therefore, that the compact method places upon the compact commissioners the important responsibility of drawing compacts in specific and unequivocal language, devoid of all possible ambiguity, and which do not attempt to define, limit or otherwise determine the extent of the powers to be exercised by the United States which is a matter for determination by the Congress through Federal legislation as required.

"The importance of insuring that future compacts more adequately reflect a clear recognition of the respective responsibilities and prerogatives of the United States and the affected States, I believe is readily apparent. In formulating provisions of interstate water compacts, which impose restrictions upon use by the United States of waters in the streams concerned, the responsibility for protecting the rights and interests of the United States rests in the first instance upon those appointed to represent the Federal Government in negotiations with the State compact commissions. The Federal Representatives also are in a position to assist the compact commission in avoiding further use of questionable or conflicting provisions similar to the aforementioned, in order to minimize the possibility of disapproval of the compact by the State legislatures or the Federal Government, or the later possibility of prolonged and costly litigation.

“F.J. Lawton

“Director”

Appendix E-1

Statistics for water samples, Yellowstone Volcanic Area, Wyoming

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)	pH (standard units)	6.8	7.0	7.4	7.6	7.7	4
	Specific conductance (µS/cm)	168	173	180	215	247	4
	Hardness (as $CaCO_3$)	24.0	26.5	31.0	40.0	47.0	4
	Calcium	8.2	8.5	9.4	12.0	14.0	4
	Magnesium	0.70	1.2	1.8	2.6	3.2	4
	Sodium	23.0	24.0	26.0	33.5	40.0	4
	Potassium	3.2	3.7	4.2	4.8	5.3	4
	Sodium adsorption ratio (unitless)	1.9	1.9	2.2	2.5	2.5	4
	Alkalinity (as $CaCO_3$)	54.9	56.6	60.6	80.7	98.4	4
	Chloride	11.0	11.5	12.0	16.5	21.0	4
	Fluoride	2.3	2.4	2.7	3.0	3.2	4
	Silica	40.0	41.0	43.0	45.5	47.0	4
	Sulfate	2.5	3.1	5.2	6.9	7.0	4
	Total dissolved solids	131	135	147	202	248	4
	Aluminum	50.0	--	--	--	300	2
	Arsenic	20.0	--	--	--	50.0	2
	Barium	16.0	--	--	--	--	1
	Beryllium	<0.30	--	--	--	--	1
	Boron	50.0	--	100	--	150	3
	Cadmium	<30.0	--	--	--	--	1
	Chromium	<3.0	--	--	--	--	1
	Cobalt	<2.0	--	--	--	--	1
	Copper	2.0	--	--	--	20.0	2
	Iron	31.0	--	--	--	--	1
	Iron, unfiltered	60.0	--	130	--	160	3
	Lead	<1.0	--	--	--	--	1
	Lithium	34.0	--	--	--	40.0	2
	Manganese	<2.0	--	--	--	20.0	2
	Molybdenum	4.0	--	--	--	--	1
	Nickel	<2.0	--	--	--	--	1
	Selenium	2.0	--	--	--	--	1
	Strontium	24.0	--	--	--	--	1
	Vanadium	<2.0	--	--	--	--	1
	Zinc	<120	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	3.6	--	--	--	3.8	2
	Uranium	--	--	--	--	<0.40	2

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers (wells)	pH (standard units)	7.6	--	7.8	--	7.9	3
	Specific conductance (µS/cm)	330	--	--	--	--	1
	Hardness (as $CaCO_3$)	178	--	182	--	190	3
	Calcium	48.0	--	50.0	--	51.9	3
	Magnesium	12.7	--	14.0	--	15.7	3
	Sodium	1.4	--	1.5	--	1.8	3
	Potassium	0.80	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.05	--	0.05	--	0.06	3
	Alkalinity (as $CaCO_3$)	169	--	172	--	174	3
	Chloride	0.10	--	1.3	--	1.5	3
	Fluoride	0.20	--	--	--	--	1
	Silica	15.0	--	--	--	--	1
	Sulfate	3.1	--	3.8	--	3.9	3
	Total dissolved solids	143	--	192	--	198	3
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.92	--	1.1	--	1.8	3
	Nitrate (as N)	1.1	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	3.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Quaternary glacial-deposit aquifers (wells)	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	110	--	--	--	--	1
	Hardness (as $CaCO_3$)	47.7	--	--	--	--	1
	Calcium	13.0	--	--	--	--	1
	Magnesium	3.7	--	--	--	--	1
	Sodium	4.0	--	--	--	--	1
	Potassium	0.90	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.25	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	55.0	--	--	--	--	1
	Chloride	0.40	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers (wells)—Continued	Silica	32.0	--	--	--	--	1
	Sulfate	1.4	--	--	--	--	1
	Total dissolved solids	91.0	--	--	--	--	1
	Ammonia (as N)	0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.39	--	--	--	--	1
	Nitrate (as N)	0.39	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	1.0	--	--	--	--	1
	Iron	30.0	--	--	--	--	1
	Lead	3.0	--	--	--	--	1
	Manganese	16.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	980	--	--	--	--	1
Quaternary and Tertiary volcanic rocks (basalt flows) (wells)	pH (standard units)	7.2	--	--	--	--	1
	Specific conductance (µS/cm)	90.0	--	--	--	--	1
	Hardness (as $CaCO_3$)	30.0	--	--	--	--	1
	Calcium	10.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	4.3	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.35	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	32.8	--	--	--	--	1
	Chloride	1.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	23.0	--	--	--	--	1
	Sulfate	0.80	--	--	--	--	1
	Total dissolved solids	69.0	--	--	--	--	1
	Iron, unfiltered	20.0	--	--	--	--	1
Quaternary and Tertiary volcanic rocks (rhyolite flows) (hot springs)	pH (standard units)	5.6	6.8	7.3	8.0	9.5	73
	Specific conductance (µS/cm)	835	940	1,180	1,520	1,650	8
	Hardness (as $CaCO_3$)	27.0	--	--	--	30.0	2
	Calcium	0.30	0.90	2.9	4.4	10.0	74
	Magnesium	0.01	0.05	0.05	0.19	1.0	73

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (rhyolite flows) (hot springs)—Continued	Sodium	62.0	170	295	333	440	75
	Potassium	4.4	10.0	11.7	14.8	39.0	75
	Sodium adsorption ratio (unitless)	7.2	22.9	46.0	87.7	186	74
	Alkalinity (as $CaCO_3$)	44.3	230	307	432	737	74
	Chloride	36.0	87.0	123	183	363	75
	Fluoride	0.10	15.2	18.6	20.5	38.0	75
	Silica	98.0	181	230	286	415	74
	Sulfate	4.0	13.0	38.0	50.0	180	74
	Total dissolved solids	298	649	1,000	1,140	1,470	74
	Aluminum	--	150	230	290	470	22
	Arsenic	100	--	--	--	--	1
	Barium	--	--	--	--	<500	24
	Boron	--	1,400	1,900	2,300	8,200	75
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<100	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	<50.0	--	--	--	50	44
	Lead	<100	--	--	--	--	1
	Lithium	--	1,100	1,300	1,600	6,700	73
	Manganese	--	35.0	80.0	115	310	24
	Mercury	29.0	--	--	--	--	1
	Nickel	<100	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	--	--	--	--	<100	23
	Zinc	--	9.7	13.1	20.0	30.0	14
Quaternary and Tertiary volcanic rocks (rhyolite flows) (springs)	pH (standard units)	6.2	--	--	--	6.4	2
	Specific conductance (µS/cm)	16.0	--	--	--	47.0	2
	Hardness (as $CaCO_3$)	4.0	--	--	--	15.0	2
	Calcium	1.4	--	--	--	4.8	2
	Magnesium	0.10	--	--	--	0.70	2
	Sodium	1.3	--	--	--	3.0	2
	Potassium	0.90	--	--	--	1.5	2
	Sodium adsorption ratio (unitless)	0.30	--	--	--	0.30	2
	Alkalinity (as $CaCO_3$)	7.0	--	--	--	19.0	2
	Chloride	0.30	--	--	--	0.60	2
	Fluoride	1.3	--	--	--	--	1
	Silica	16.0	--	--	--	31.0	2
	Sulfate	1.4	--	--	--	2.4	2
	Total dissolved solids	26.0	--	--	--	54.0	2

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (hot springs)	pH (standard units)	4.6	7.6	8.1	8.7	9.9	10
	Calcium	0.90	0.94	1.2	3.3	10.0	11
	Magnesium	0.02	0.03	0.09	0.10	0.15	11
	Sodium	198	310	372	400	405	11
	Potassium	9.1	9.7	12.8	16.2	34.8	11
	Sodium adsorption ratio (unitless)	26.7	34.5	90.8	105	111	11
	Alkalinity (as $CaCO_3$)	122	258	270	318	338	7
	Chloride	140	236	295	310	360	11
	Fluoride	12.0	17.0	22.0	26.0	35.0	11
	Silica	181	214	271	330	340	11
	Sulfate	110	116	140	157	170	11
	Total dissolved solids	734	1,080	1,210	1,340	1,430	11
	Phosphorus (as P)	--	--	--	--	<2.0	4
	Aluminum	--	98.0	205	260	260	4
	Antimony	--	35.5	48.0	53.5	59.0	4
	Arsenic	--	1,045	1,400	1,500	1,600	4
	Barium	--	1.3	2.0	3.5	5.0	4
	Beryllium	--	2.6	4.0	4.7	5.1	4
	Boron	--	2,700	3,200	3,600	4,170	11
	Cadmium	--	--	--	--	<0.02	4
	Chromium	--	--	--	--	<1.0	4
	Cobalt	--	--	--	--	<0.02	4
	Copper	--	--	--	--	<0.50	4
	Iron	--	--	--	--	<30.0	4
	Lead	--	--	--	--	<0.05	4
	Lithium	--	3,100	4,600	6,200	6,400	11
	Manganese	--	0.27	0.59	14.5	28.0	4
	Mercury	--	0.05	0.05	0.06	0.06	4
	Molybdenum	--	74.0	95.0	98.0	100	4
	Nickel	--	--	--	--	<0.10	4
	Selenium	--	3.3	4.3	5.0	5.5	4
	Strontium	--	8.0	17.5	23.0	24.0	4
	Vanadium	--	2.0	2.0	2.5	3.0	4
	Zinc	--	--	--	--	<0.50	4
	Uranium	0.01	--	0.04	--	0.05	3
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (springs)	pH (standard units)	6.1	6.7	7.0	7.1	7.2	6
	Specific conductance (µS/cm)	20.0	24.0	60.0	110	167	6
	Hardness (as $CaCO_3$)	6.2	7.3	15.0	18.0	25.0	6
	Calcium	1.8	2.1	5.1	6.2	7.4	6
	Magnesium	0.42	0.50	0.56	0.60	1.6	6

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (springs)—Continued	Sodium	1.1	1.1	2.9	16.0	30.0	6
	Potassium	0.60	0.70	1.1	3.2	4.0	6
	Sodium adsorption ratio (unitless)	0.18	0.19	0.27	1.8	3.4	6
	Alkalinity (as $CaCO_3$)	9.0	11.0	25.4	40.2	57.0	6
	Chloride	0.10	0.20	0.55	7.0	20.0	6
	Fluoride	0.10	0.10	0.20	0.60	1.6	5
	Silica	10.0	11.0	26.5	37.0	67.0	6
	Sulfate	0.80	0.80	0.80	1.1	1.6	6
	Total dissolved solids	22.0	22.0	55.0	126	133	6
	Ammonia (as N)	<0.01	--	--	--	0.02	2
	Nitrate plus nitrite (as N)	<0.05	--	--	--	0.13	2
	Nitrate (as N)	<0.05	--	--	--	0.13	2
	Nitrite (as N)	--	--	--	--	<0.01	2
	Orthophosphate (as P)	--	--	--	--	<0.01	2
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
	Boron	60.0	--	--	--	180	2
	Iron, unfiltered	10.0	--	20.0	--	270	3
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (wells)	pH (standard units)	7.9	8.0	8.0	8.1	8.1	6
	Specific conductance (µS/cm)	184	--	308	--	385	3
	Hardness (as $CaCO_3$)	143	144	152	187	190	5
	Calcium	40.0	40.4	42.5	48.0	56.0	5
	Magnesium	10.5	10.5	11.0	13.0	13.0	5
	Sodium	0.97	1.0	1.0	1.0	3.2	5
	Potassium	0.70	--	--	--	1.0	2
	Sodium adsorption ratio (unitless)	0.03	0.03	0.04	0.04	0.10	5
	Alkalinity (as $CaCO_3$)	136	136	144	155	194	5
	Chloride	0.73	0.74	0.89	1.8	6.8	6
	Fluoride	0.10	--	--	--	0.10	2
	Silica	14.0	--	--	--	17.0	2
	Sulfate	0.80	2.0	3.1	3.4	5.0	6
	Total dissolved solids	133	138	150	198	209	5
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	--	0.10	0.20	0.21	0.90	5
	Nitrate (as N)	0.09	--	--	--	--	1
	Nitrite (as N)	0.01	--	--	--	--	1
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Aluminum	<100	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	<5.0	--	--	--	--	1

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (wells)—Continued	Barium	<100	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Boron	--	--	--	--	<100	2
	Cadmium	<0.50	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	<50.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	70.0	2
	Mercury	<0.50	--	--	--	--	1
	Nickel	<20.0	--	--	--	--	1
	Selenium	<5.0	--	--	--	--	1
	Zinc	<10.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	2.7	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.30	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Uranium	0.004	--	--	--	--	1
Quaternary obsidian sand and gravel deposits underlying Lava Creek Tuff (Member B) of Yellowstone Group (wells)	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	253	--	--	--	--	1
	Hardness (as $CaCO_3$)	59.0	--	--	--	--	1
	Calcium	14.0	--	--	--	--	1
	Magnesium	5.8	--	--	--	--	1
	Sodium	26.0	--	--	--	--	1
	Potassium	3.5	--	--	--	--	1
	Sodium adsorption ratio (unitless)	1.5	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	90.2	--	--	--	--	1
	Chloride	16.0	--	--	--	--	1
	Fluoride	2.8	--	--	--	--	1
	Silica	42.0	--	--	--	--	1
	Sulfate	3.0	--	--	--	--	1
	Total dissolved solids	183	--	--	--	--	1
	Boron	480	--	--	--	--	1
	Iron, unfiltered	130	--	--	--	--	1
	Manganese	40.0	--	--	--	--	1
Madison aquifer (hot springs)	pH (standard units)	7.6	--	7.8	--	7.9	3
	Calcium	77.5	--	150	--	185	3
	Magnesium	14.6	--	29.0	--	35.0	3
	Sodium	143	--	290	--	380	3

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (hot springs)—Continued	Potassium	24.0	--	52.5	--	68.0	3
	Sodium adsorption ratio (unitless)	3.9	--	5.7	--	6.7	3
	Alkalinity (as $CaCO_3$)	298	--	536	--	539	3
	Chloride	139	--	145	--	201	3
	Fluoride	3.0	--	3.5	--	4.6	3
	Silica	60.8	--	60.8	--	61.6	3
	Sulfate	49.5	--	493	--	702	3
	Total dissolved solids	695	--	1,550	--	1,960	3
	Boron	1,700	--	3,000	--	4,000	3
	Lithium	950	--	1,450	--	1,950	3
Madison aquifer (springs)	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	450	--	--	--	--	1
	Hardness (as $CaCO_3$)	242	--	--	--	--	1
	Calcium	72.0	--	--	--	--	1
	Magnesium	15.0	--	--	--	--	1
	Sodium	1.0	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.03	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	241	--	--	--	--	1
	Chloride	2.0	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	6.6	--	--	--	--	1
	Sulfate	2.4	--	--	--	--	1
	Total dissolved solids	245	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.21	--	--	--	--	1
	Nitrate (as N)	0.21	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
Madison aquifer (wells)	pH (standard units)	7.7	--	--	--	8.0	2
	Specific conductance (µS/cm)	242	--	--	--	258	2
	Hardness (as $CaCO_3$)	120	--	--	--	132	2
	Calcium	27.0	--	--	--	34.0	2
	Magnesium	11.0	--	--	--	13.0	2
	Sodium	0.50	--	--	--	0.50	2
	Potassium	0.90	--	--	--	1.8	2
	Sodium adsorption ratio (unitless)	0.02	--	--	--	0.02	2

Appendix E–1. Summary statistics for water samples, Yellowstone Volcanic Area, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (wells)—Continued	Alkalinity (as $CaCO_3$)	114	--	--	--	126	2
	Chloride	1.0	--	--	--	1.7	2
	Silica	5.3	--	--	--	7.2	2
	Sulfate	4.9	--	--	--	5.8	2
	Total dissolved solids	128	--	--	--	138	2
	Boron	10.0	--	--	--	10.0	2
Darby aquifer (wells)	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	328	--	--	--	--	1
	Hardness (as $CaCO_3$)	177	--	--	--	--	1
	Calcium	51.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	0.80	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.03	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	178	--	--	--	--	1
	Chloride	2.0	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	6.5	--	--	--	--	1
	Sulfate	2.1	--	--	--	--	1
	Total dissolved solids	183	--	--	--	--	1
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.22	--	--	--	--	1
	Nitrate (as N)	0.22	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1

Appendix E-2

Statistics for water samples, Northern Ranges, Wyoming

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (springs)	pH (standard units)	8.2	--	--	--	--	1
	Specific conductance (µS/cm)	285	--	--	--	--	1
	Hardness (as $CaCO_3$)	150	--	--	--	--	1
	Calcium	48.0	--	--	--	--	1
	Magnesium	6.7	--	--	--	--	1
	Sodium	1.1	--	--	--	--	1
	Potassium	0.50	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.04	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	125	--	--	--	--	1
	Chloride	1.8	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	5.1	--	--	--	--	1
	Sulfate	20.0	--	--	--	--	1
	Total dissolved solids	159	--	--	--	--	1
Quaternary alluvial aquifers (wells)	Dissolved oxygen	1.2	--	--	--	3.8	2
	pH (standard units)	6.7	7.5	7.6	8.0	8.0	5
	Specific conductance (µS/cm)	193	257	291	353	433	5
	Hardness (as $CaCO_3$)	142	--	166	--	221	3
	Calcium	35.0	--	37.0	--	57.0	3
	Magnesium	12.0	--	19.0	--	19.0	3
	Sodium	2.4	--	5.5	--	6.0	3
	Potassium	1.0	--	2.0	--	5.3	3
	Sodium adsorption ratio (unitless)	0.09	--	0.18	--	0.19	3
	Alkalinity (as $CaCO_3$)	97.0	121	148	165	180	4
	Chloride	2.1	--	2.8	--	3.3	3
	Fluoride	0.10	--	0.40	--	0.60	3
	Silica	10.0	--	14.0	--	48.0	3
	Sulfate	7.4	--	9.1	--	75.0	3
	Total dissolved solids	160	--	233	--	267	3
	Ammonia (as N)	--	0.01	0.02	0.04	0.18	5
	Nitrate plus nitrite (as N)	--	0.08	0.10	0.13	0.92	5
	Nitrate (as N)	--	0.08	0.10	0.13	0.92	5
	Nitrite (as N)	--	--	--	--	<0.10	5
	Orthophosphate (as P)	<0.01	--	--	--	0.14	5
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Aluminum	--	--	--	--	10.0	2
	Arsenic	<1.0	--	--	--	3.0	2
	Boron	10.0	--	--	--	30.0	2

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)—Continued	Cadmium	<10.0	--	--	--	--	1
	Chromium	--	--	--	--	<1.0	2
	Copper	--	--	--	--	<1.0	2
	Iron	<3.0	--	--	--	--	1
	Lead	--	--	--	--	<1.0	2
	Manganese	<1.0	--	--	--	--	1
	Mercury	--	--	--	--	<0.01	2
	Selenium	--	--	--	--	<1.0	2
	Zinc	<3.0	--	--	--	--	1
Quaternary terrace-deposit aquifers (springs)	Hardness (as $CaCO_3$)	89.0	--	--	--	--	1
	Calcium	27.0	--	--	--	--	1
	Magnesium	5.3	--	--	--	--	1
	Sodium	18.0	--	--	--	--	1
	Potassium	3.4	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.80	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	98.0	--	--	--	--	1
	Chloride	9.3	--	--	--	--	1
	Fluoride	1.4	--	--	--	--	1
	Silica	27.0	--	--	--	--	1
	Sulfate	21.0	--	--	--	--	1
	Total dissolved solids	172	--	--	--	--	1
	Ammonia plus organic nitrogen, unfiltered (as N)	0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.09	--	--	--	--	1
	Total nitrogen, unfiltered (as N)	0.19	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
	Dissolved organic carbon	15.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
Quaternary terrace-deposit aquifers (wells)	pH (standard units)	7.5	--	--	--	8.2	2
	Specific conductance (µS/cm)	280	--	--	--	940	2
	Hardness (as $CaCO_3$)	37.0	--	--	--	110	2
	Calcium	13.0	--	--	--	34.0	2
	Magnesium	0.90	--	--	--	4.7	2
	Sodium	14.0	--	--	--	190	2
	Potassium	3.0	--	--	--	12.0	2
	Sodium adsorption ratio (unitless)	0.60	--	--	--	13.7	2
	Alkalinity (as $CaCO_3$)	119	--	--	--	258	2
	Chloride	7.4	--	--	--	110	2

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers (wells)—Continued	Fluoride	1.0	--	--	--	5.0	2
	Silica	27.0	--	--	--	95.0	2
	Sulfate	9.9	--	--	--	22.0	2
	Total dissolved solids	173	--	--	--	601	2
	Boron	120	--	--	--	510	2
	Iron	10.0	--	--	--	--	1
	Iron, unfiltered	70.0	--	--	--	--	1
Quaternary glacial-deposit aquifers (springs)	pH (standard units)	8.0	--	--	--	8.2	2
	Specific conductance (µS/cm)	315	--	--	--	385	2
	Hardness (as $CaCO_3$)	170	--	--	--	200	2
	Calcium	49.0	--	--	--	60.0	2
	Magnesium	11.0	--	--	--	12.0	2
	Sodium	1.1	--	--	--	1.6	2
	Potassium	0.50	--	--	--	2.1	2
	Sodium adsorption ratio (unitless)	0.04	--	--	--	0.05	2
	Alkalinity (as $CaCO_3$)	169	--	--	--	198	2
	Chloride	0.70	--	--	--	1.5	2
	Fluoride	0.10	--	--	--	0.10	2
	Silica	6.5	--	--	--	21.0	2
	Sulfate	0.80	--	--	--	3.3	2
	Total dissolved solids	173	--	--	--	219	2
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.25	--	--	--	--	1
	Nitrate (as N)	0.25	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Boron	10.0	--	--	--	20.0	2
	Iron	20.0	--	--	--	--	1
Quaternary glacial-deposit aquifers (wells)	Dissolved oxygen	7.7	--	--	--	8.6	2
	pH (standard units)	7.5	7.5	7.7	7.8	8.0	6
	Specific conductance (µS/cm)	280	319	368	403	464	6
	Hardness (as $CaCO_3$)	150	160	171	185	198	4
	Calcium	43.0	45.0	49.0	52.0	53.0	4
	Magnesium	9.2	9.4	11.3	15.0	17.0	4
	Sodium	1.4	2.1	3.0	4.3	5.3	4
	Potassium	0.90	0.90	1.3	1.9	2.1	4
	Sodium adsorption ratio (unitless)	0.05	0.07	0.10	0.14	0.16	4
	Alkalinity (as $CaCO_3$)	151	159	185	207	234	6
	Chloride	0.10	0.90	1.9	3.7	5.3	4

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers (wells)—Continued	Fluoride	0.10	0.15	0.20	0.20	0.20	4
	Silica	5.9	8.0	12.0	17.5	21.0	4
	Sulfate	0.80	1.2	2.5	4.2	4.9	4
	Total dissolved solids	162	165	178	209	228	4
	Ammonia (as N)	<0.01	--	--	--	0.03	2
	Nitrate plus nitrite (as N)	0.06	--	--	--	0.52	2
	Nitrate (as N)	0.06	--	--	--	0.52	2
	Nitrite (as N)	--	--	--	--	<0.01	2
	Orthophosphate (as P)	<0.01	--	--	--	0.02	2
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Boron	10.0	--	20.0	--	50.0	3
	Iron	10.0	--	--	--	20.0	2
	Iron, unfiltered	10.0	--	--	--	--	1
Quaternary landslide deposits (springs)	pH (standard units)	8.2	--	--	--	8.3	2
	Calcium	20.2	--	31.5	--	72.3	3
	Magnesium	5.6	--	10.6	--	18.6	3
	Sodium	0.46	--	0.69	--	0.85	3
	Potassium	0.23	--	0.55	--	0.59	3
	Sodium adsorption ratio (unitless)	0.02	--	0.02	--	0.04	3
	Alkalinity (as $CaCO_3$)	90.3	--	154	--	331	3
	Chloride	0.18	--	0.39	--	5.7	3
	Fluoride	0.84	--	--	--	0.84	2
	Silica	0.71	--	1.7	--	4.1	3
	Sulfate	7.3	--	7.7	--	14.9	3
	Total dissolved solids	79.8	--	127	--	276	3
Quaternary landslide deposits (wells)	pH (standard units)	8.7	--	--	--	--	1
	Specific conductance (µS/cm)	875	--	--	--	--	1
	Hardness (as $CaCO_3$)	60.0	--	--	--	--	1
	Calcium	17.0	--	--	--	--	1
	Magnesium	4.6	--	--	--	--	1
	Sodium	180	--	--	--	--	1
	Potassium	1.4	--	--	--	--	1
	Sodium adsorption ratio (unitless)	10.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	290	--	--	--	--	1
	Chloride	4.2	--	--	--	--	1
	Fluoride	0.80	--	--	--	--	1
	Silica	9.9	--	--	--	--	1
	Sulfate	82.0	--	--	--	--	1
	Total dissolved solids	495	--	--	--	--	1

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary landslide deposits (wells)—Continued	Boron	190	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (springs)	pH (standard units)	6.6	--	--	--	--	1
	Specific conductance (µS/cm)	74.0	--	--	--	--	1
	Hardness (as $CaCO_3$)	29.5	--	--	--	--	1
	Calcium	8.7	--	--	--	--	1
	Magnesium	1.9	--	--	--	--	1
	Sodium	2.8	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.22	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	36.0	--	--	--	--	1
	Chloride	0.10	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	23.0	--	--	--	--	1
	Sulfate	1.7	--	--	--	--	1
	Total dissolved solids	61.0	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.07	--	--	--	--	1
	Nitrate (as N)	0.07	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
Quaternary and Tertiary volcanic rocks (Yellowstone Group) (wells)	Dissolved oxygen	4.5	--	--	--	5.1	2
	pH (standard units)	7.9	--	--	--	8.0	2
	Specific conductance (µS/cm)	392	--	--	--	483	2
	Alkalinity (as $CaCO_3$)	160	--	--	--	190	2
	Ammonia (as N)	0.02	--	--	--	0.04	2
	Nitrate plus nitrite (as N)	0.07	--	--	--	0.10	2
	Nitrate (as N)	0.07	--	--	--	0.10	2
	Nitrite (as N)	--	--	--	--	<0.01	2
	Orthophosphate (as P)	0.02	--	--	--	0.02	2
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks) (wells)	pH (standard units)	7.8	--	--	--	7.9	2
	Specific conductance (µS/cm)	475	--	--	--	490	2
	Hardness (as $CaCO_3$)	220	--	--	--	230	2
	Calcium	60.0	--	--	--	62.0	2
	Magnesium	16.0	--	--	--	19.0	2
	Sodium	9.6	--	--	--	10.0	2
	Potassium	4.4	--	--	--	4.7	2
	Sodium adsorption ratio (unitless)	0.28	--	--	--	0.29	2

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks) (wells)—Continued	Alkalinity (as $CaCO_3$)	229	--	--	--	235	2
	Chloride	1.5	--	--	--	1.5	2
	Fluoride	0.20	--	--	--	0.30	2
	Silica	45.0	--	--	--	62.0	2
	Sulfate	12.0	--	--	--	13.0	2
	Total dissolved solids	296	--	--	--	306	2
Frontier aquifer (springs)	pH (standard units)	7.7	--	7.7	--	8.5	3
	Specific conductance (µS/cm)	113	--	550	--	690	3
	Hardness (as $CaCO_3$)	46.9	--	150	--	210	3
	Calcium	15.0	--	51.0	--	75.0	3
	Magnesium	2.3	--	4.1	--	5.7	3
	Sodium	3.9	--	68.0	--	74.0	3
	Potassium	0.40	--	1.2	--	2.1	3
	Sodium adsorption ratio (unitless)	0.25	--	2.2	--	2.5	3
	Alkalinity (as $CaCO_3$)	46.0	--	203	--	286	3
	Chloride	0.50	--	1.8	--	1.8	3
	Fluoride	0.20	--	0.40	--	0.40	3
	Silica	9.7	--	12.0	--	17.0	3
	Sulfate	12.0	--	73.0	--	74.0	3
	Total dissolved solids	80.0	--	338	--	416	3
	Ammonia (as N)	0.04	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.31	--	--	--	--	1
	Nitrate (as N)	0.31	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Boron	90.0	--	--	--	90.0	2
	Iron	20.0	--	--	--	--	1
Twin Creek aquifer (springs)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	446	--	--	--	--	1
	Hardness (as $CaCO_3$)	240	--	--	--	--	1
	Calcium	72.0	--	--	--	--	1
	Magnesium	14.0	--	--	--	--	1
	Sodium	3.3	--	--	--	--	1
	Potassium	0.60	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.10	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	240	--	--	--	--	1
	Chloride	1.4	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	12.0	--	--	--	--	1

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Twin Creek aquifer (springs)—Continued	Sulfate	8.3	--	--	--	--	1
	Total dissolved solids	256	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.15	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Iron, unfiltered	10.0	--	--	--	--	1
Gypsum Spring confining unit (springs)	Calcium	401	--	--	--	--	1
	Magnesium	98.5	--	--	--	--	1
	Sodium	106	--	--	--	--	1
	Potassium	2.7	--	--	--	--	1
	Sodium adsorption ratio (unitless)	1.2	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	6.7	--	--	--	--	1
	Chloride	21.3	--	--	--	--	1
	Silica	7.6	--	--	--	--	1
	Sulfate	1,560	--	--	--	--	1
	Total dissolved solids	2,190	--	--	--	--	1
Chugwater aquifer and confining unit (wells)	pH (standard units)	7.7	--	--	--	8.1	2
	Specific conductance (µS/cm)	290	--	--	--	1,700	2
	Hardness (as $CaCO_3$)	150	--	--	--	980	2
	Calcium	38.0	--	--	--	290	2
	Magnesium	12.0	--	--	--	63.0	2
	Sodium	1.1	--	--	--	19.0	2
	Potassium	0.50	--	--	--	2.6	2
	Sodium adsorption ratio (unitless)	0.04	--	--	--	0.26	2
	Alkalinity (as $CaCO_3$)	128	--	--	--	134	2
	Chloride	0.70	--	--	--	11.0	2
	Fluoride	0.20	--	--	--	0.80	2
	Silica	5.8	--	--	--	8.4	2
	Sulfate	13.0	--	--	--	880	2
	Total dissolved solids	153	--	--	--	1,340	2
	Boron	90.0	--	--	--	--	1
	Iron	10.0	--	--	--	60.0	2
Ankareh aquifer (springs)	pH (standard units)	7.1	--	--	--	--	1
	Specific conductance (µS/cm)	446	--	--	--	--	1
	Hardness (as CaCO3)	235	--	--	--	--	1
	Calcium	71.0	--	--	--	--	1
	Magnesium	14.0	--	--	--	--	1
	Sodium	3.2	--	--	--	--	1
	Potassium	0.70	--	--	--	--	1

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Ankareh aquifer (springs)—Continued	Sodium adsorption ratio (unitless)	0.09	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	243	--	--	--	--	1
	Chloride	2.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	12.0	--	--	--	--	1
	Sulfate	7.1	--	--	--	--	1
	Total dissolved solids	256	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.15	--	--	--	--	1
	Nitrate (as N)	0.15	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
Dinwoody aquifer and confining unit (springs)	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	455	--	--	--	--	1
	Hardness (as $CaCO_3$)	251	--	--	--	--	1
	Calcium	66.0	--	--	--	--	1
	Magnesium	21.0	--	--	--	--	1
	Sodium	3.0	--	--	--	--	1
	Potassium	0.60	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.08	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	253	--	--	--	--	1
	Chloride	2.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	13.0	--	--	--	--	1
	Sulfate	4.3	--	--	--	--	1
	Total dissolved solids	262	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.08	--	--	--	--	1
	Nitrate (as N)	0.08	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.05	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.04	--	--	--	--	1
Phosphoria aquifer (springs)	pH (standard units)	7.8	--	7.8	--	8.0	3
	Calcium	27.7	--	31.1	--	43.5	3
	Magnesium	7.4	--	9.7	--	12.2	3
	Sodium	0.18	--	0.69	--	1.8	3
	Potassium	0.08	--	0.08	--	0.08	3

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Phosphoria aquifer (springs)—Continued	Sodium adsorption ratio (unitless)	0.008	--	0.02	--	0.07	3
	Alkalinity (as $CaCO_3$)	103	--	116	--	132	3
	Chloride	0.07	--	0.07	--	1.1	3
	Fluoride	0.84	--	0.84	--	0.84	3
	Silica	0.88	--	1.4	--	1.7	3
	Sulfate	3.4	--	25.0	--	42.3	3
	Total dissolved solids	95.4	--	119	--	164	3
Tensleep aquifer (springs)	pH (standard units)	7.3	7.5	7.6	7.8	8.0	6
	Specific conductance (µS/cm)	219	--	438	--	518	3
	Hardness (as $CaCO_3$)	109	--	242	--	275	3
	Calcium	27.0	53.9	65.6	69.0	76.0	6
	Magnesium	10.0	17.0	18.8	24.4	28.0	6
	Sodium	0.23	0.23	1.2	1.6	5.9	6
	Potassium	0.08	0.08	0.44	1.4	1.7	6
	Sodium adsorption ratio (unitless)	0.006	0.007	0.03	0.07	0.15	6
	Alkalinity (as $CaCO_3$)	116	132	177	227	284	6
	Chloride	0.10	0.20	0.71	1.4	4.7	6
	Fluoride	0.10	0.20	0.52	0.84	0.84	6
	Silica	1.6	3.0	5.6	11.0	26.0	6
	Sulfate	1.5	2.2	39.1	122	140	6
	Total dissolved solids	123	233	268	300	312	6
	Ammonia (as N)	<0.01	--	--	--	0.02	3
	Nitrate plus nitrite (as N)	0.05	--	0.22	--	0.29	3
	Nitrate (as N)	0.05	--	0.22	--	0.29	3
	Nitrite (as N)	--	--	--	--	<0.01	3
	Orthophosphate (as P)	0.01	--	0.02	--	0.17	3
	Phosphorus, unfiltered (as P)	0.03	--	--	--	0.26	2
	Aluminum	20.0	--	--	--	--	1
	Arsenic	4.0	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	2.0	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	<3.0	--	--	--	--	1

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Amsden aquifer (springs)	Calcium	16.6	--	--	--	--	1
	Magnesium	3.2	--	--	--	--	1
	Sodium	0.18	--	--	--	--	1
	Potassium	0.08	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.01	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	68.9	--	--	--	--	1
	Chloride	0.11	--	--	--	--	1
	Silica	0.37	--	--	--	--	1
	Sulfate	2.1	--	--	--	--	1
	Total dissolved solids	56.3	--	--	--	--	1
Madison aquifer (springs and cave)	pH (standard units)	7.5	7.5	7.7	7.9	8.0	4
	Specific conductance (µS/cm)	156	--	--	--	--	1
	Hardness (as $CaCO_3$)	81.3	--	--	--	--	1
	Calcium	9.2	22.0	26.5	27.9	28.1	6
	Magnesium	1.2	5.1	6.9	7.4	8.9	6
	Sodium	0.18	0.18	0.23	0.60	0.76	6
	Potassium	0.08	0.08	0.12	0.20	0.43	6
	Sodium adsorption ratio (unitless)	0.008	0.008	0.02	0.03	0.03	6
	Alkalinity (as $CaCO_3$)	35.4	82.0	109	118	120	6
	Chloride	0.07	0.07	0.09	0.18	0.35	6
	Fluoride	0.20	0.52	0.84	0.84	0.84	4
	Silica	0.60	0.62	1.2	2.3	2.3	6
	Sulfate	0.48	1.3	1.8	4.3	13.0	6
	Total dissolved solids	31.5	82.8	89.0	101	106	6
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.19	--	--	--	--	1
	Nitrate (as N)	0.19	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
Bighorn aquifer (springs)	pH (standard units)	7.3	--	8.0	--	8.2	3
	Specific conductance (µS/cm)	179	--	--	--	202	2
	Hardness (as $CaCO_3$)	99.9	--	--	--	105	2
	Calcium	11.8	--	26.0	--	28.0	3
	Magnesium	2.4	--	8.4	--	8.5	3
	Sodium	0.18	--	0.50	--	0.60	3
	Potassium	0.08	--	0.30	--	0.40	3
	Sodium adsorption ratio (unitless)	0.01	--	0.02	--	0.03	3

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bighorn aquifer (springs)—Continued	Alkalinity (as $CaCO_3$)	46.4	--	92.0	--	107	3
	Chloride	0.07	--	0.10	--	0.10	3
	Fluoride	0.20	--	0.30	--	0.84	3
	Silica	0.28	--	2.8	--	3.9	3
	Sulfate	0.48	--	1.1	--	2.4	3
	Total dissolved solids	37.1	--	96.0	--	107	3
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.16	--	--	--	--	1
	Nitrate (as N)	0.16	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	0.01	2
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	2.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Bighorn aquifer (wells)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	440	--	--	--	--	1
	Hardness (as $CaCO_3$)	4.0	--	--	--	--	1
	Calcium	1.7	--	--	--	--	1
	Sodium	109	--	--	--	--	1
	Potassium	0.20	--	--	--	--	1
	Sodium adsorption ratio (unitless)	23.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	226	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	4.1	--	--	--	--	1
	Total dissolved solids	270	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
Gallatin aquifer and confining unit (springs)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	2,380	--	--	--	--	1
	Hardness (as $CaCO_3$)	1,600	--	--	--	--	1
	Calcium	20.6	--	--	--	430	2

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

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Hydrogeologic unit	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Gallatin aquifer and confining unit (springs)—Continued	Magnesium	5.4	--	--	--	120	2
	Sodium	0.25	--	--	--	28.0	2
	Potassium	0.23	--	--	--	13.0	2
	Sodium adsorption ratio (unitless)	0.01	--	--	--	0.31	2
	Alkalinity (as $CaCO_3$)	92.7	--	--	--	160	2
	Chloride	0.11	--	--	--	3.9	2
	Fluoride	0.50	--	--	--	--	1
	Silica	0.05	--	--	--	26.0	2
	Sulfate	3.6	--	--	--	1,600	2
	Total dissolved solids	75.8	--	--	--	2,480	2
	Boron	60.0	--	--	--	--	1
Gros Ventre aquifer and confining unit (springs)	pH (standard units)	7.2	7.5	7.8	8.0	8.1	4
	Specific conductance (µS/cm)	186	--	--	--	260	2
	Hardness (as $CaCO_3$)	88.8	--	--	--	135	2
	Calcium	24.0	27.5	28.7	34.5	36.0	5
	Magnesium	4.9	7.0	10.7	11.0	14.5	5
	Sodium	0.18	0.18	0.44	0.60	2.0	5
	Potassium	0.08	0.30	0.35	0.39	0.70	5
	Sodium adsorption ratio (unitless)	0.007	0.008	0.02	0.02	0.09	5
	Alkalinity (as $CaCO_3$)	94.0	98.2	137	139	188	5
	Chloride	0.07	0.07	0.39	1.1	2.1	5
	Fluoride	0.10	0.10	0.47	0.84	0.84	4
	Silica	0.78	0.83	1.8	2.8	7.8	5
	Sulfate	0.48	2.1	3.3	3.5	5.8	5
	Total dissolved solids	86.8	102	107	140	148	5
	Ammonia (as N)	<0.01	--	--	--	0.02	2
	Nitrate plus nitrite (as N)	0.12	--	--	--	0.15	2
	Nitrate (as N)	0.12	--	--	--	0.15	2
	Nitrite (as N)	--	--	--	--	<0.01	2
	Orthophosphate (as P)	<0.01	--	--	--	0.01	2
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Iron	30.0	--	--	--	--	1
Flathead aquifer (hot springs)	pH (standard units)	8.3	--	--	--	8.3	2
	Specific conductance (µS/cm)	1,050	--	--	--	--	1
	Hardness (as $CaCO_3$)	110	--	--	--	--	1
	Calcium	24.7	--	--	--	32.0	2
	Magnesium	2.5	--	--	--	6.4	2
	Sodium	180	--	--	--	266	2

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Flathead aquifer (hot springs)—Continued	Potassium	8.8	--	--	--	17.1	2
	Sodium adsorption ratio (unitless)	7.6	--	--	--	13.6	2
	Alkalinity (as $CaCO_3$)	191	--	--	--	200	2
	Chloride	140	--	--	--	234	2
	Fluoride	6.0	--	--	--	6.8	2
	Silica	39.4	--	--	--	49.0	2
	Sulfate	150	--	--	--	180	2
	Total dissolved solids	670	--	--	--	826	2
	Arsenic	<50.0	--	--	--	--	1
	Barium	<500	--	--	--	--	1
	Boron	610	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<100	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Lead	<100	--	--	--	--	1
	Manganese	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Nickel	<100	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	<20.0	--	--	--	--	1
Precambrian basal confining unit (springs)	pH (standard units)	6.4	6.5	6.8	7.2	7.4	4
	Specific conductance (µS/cm)	17.0	75.0	174	797	1,380	4
	Hardness (as $CaCO_3$)	4.8	34.9	87.5	304	498	4
	Calcium	1.5	8.2	18.6	30.0	160	7
	Magnesium	0.25	0.73	2.3	8.6	24.0	7
	Sodium	0.80	1.2	1.4	2.9	91.0	7
	Potassium	0.30	0.39	0.86	0.98	25.0	7
	Sodium adsorption ratio (unitless)	0.05	0.07	0.10	0.28	1.8	7
	Alkalinity (as $CaCO_3$)	8.0	25.0	63.5	113	622	7
	Chloride	0.10	0.10	0.21	0.35	100	6
	Fluoride	0.10	0.10	0.10	0.15	0.20	4
	Silica	2.1	2.7	9.5	14.0	39.0	7
	Sulfate	0.80	1.6	6.8	15.8	17.0	7
	Total dissolved solids	19.0	32.8	67.7	126	829	7
	Ammonia (as N)	<0.01	--	--	--	0.08	3
	Nitrate plus nitrite (as N)	<0.05	--	--	--	0.13	3
	Nitrate (as N)	<0.05	--	--	--	0.13	3
	Nitrite (as N)	--	--	--	--	<0.01	3

Appendix E–2. Summary statistics for water samples, Northern Ranges, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Precambrian basal confining unit (springs)—Continued	Orthophosphate (as P)	--	--	--	--	<0.01	3
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	0.02	2
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	10.0	--	--	--	20.0	2
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1

Appendix E-3

Statistics for water samples, Jackson Hole, Wyoming

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (springs)	Dissolved oxygen	6.3	--	--	--	--	1
	pH (standard units)	7.3	--	--	--	7.5	2
	Specific conductance (µS/cm)	237	--	--	--	724	2
	Hardness (as $CaCO_3$)	344	--	--	--	--	1
	Calcium	100	--	--	--	--	1
	Magnesium	23.0	--	--	--	--	1
	Sodium	27.0	--	--	--	--	1
	Potassium	2.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.63	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	279	--	--	--	--	1
	Chloride	2.6	--	--	--	4.7	2
	Fluoride	0.20	--	--	--	--	1
	Silica	15.0	--	--	--	--	1
	Sulfate	130	--	--	--	--	1
	Total dissolved solids	470	--	--	--	--	1
	Ammonia (as N)	--	--	--	--	<0.01	2
	Nitrate plus nitrite (as N)	0.08	--	--	--	0.34	2
	Nitrate (as N)	0.08	--	--	--	0.34	2
	Nitrite (as N)	--	--	--	--	<0.01	2
	Orthophosphate (as P)	<0.01	--	--	--	0.01	2
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
Quaternary alluvial aquifers (wells)	Dissolved oxygen	0.10	3.1	5.2	7.0	9.2	39
	pH (standard units)	6.0	7.5	7.7	7.9	8.8	97
	Specific conductance (µS/cm)	34.0	273	401	467	892	94
	Hardness (as $CaCO_3$)	10.0	130	187	230	422	68
	Calcium	2.1	37.5	54.5	66.0	126	68
	Magnesium	1.2	8.0	12.5	19.0	49.6	68
	Sodium	1.0	4.2	6.3	8.4	150	71
	Potassium	0.50	1.3	1.6	2.3	9.0	68
	Sodium adsorption ratio (unitless)	0.02	0.12	0.20	0.28	20.5	68
	Alkalinity (as $CaCO_3$)	12.0	132	174	211	353	79
	Chloride	0.30	1.8	2.8	4.2	34.0	81
	Fluoride	0.03	0.11	0.20	0.30	3.6	71
	Silica	6.5	10.0	13.0	16.0	51.0	62
	Sulfate	1.5	8.0	21.3	48.5	271	72
	Total dissolved solids	52.0	161	250	277	628	71
	Ammonia (as N)	--	0.005	0.009	0.02	0.04	54
	Ammonia plus organic nitrogen, unfiltered (as N)	0.10	--	--	--	0.27	2

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)—Continued	Nitrate plus nitrite (as N)	--	0.08	0.17	0.36	2.9	64
	Nitrate (as N)	--	0.08	0.16	0.31	2.4	56
	Nitrite (as N)	--	--	--	--	<0.10	57
	Organic nitrogen, unfiltered (as N)	0.14	--	0.15	--	0.26	3
	Total nitrogen, unfiltered (as N)	0.25	--	--	--	0.36	2
	Orthophosphate (as P)	--	0.006	0.01	0.02	0.13	53
	Phosphorus (as P)	--	0.008	0.02	0.03	0.06	16
	Phosphorus, unfiltered (as P)	--	0.01	0.02	0.03	0.06	10
	Dissolved organic carbon	--	0.30	0.40	0.60	1.9	15
	Aluminum	--	1.8	5.1	14.0	260	14
	Antimony	--	--	--	--	<1.0	3
	Arsenic	--	0.77	1.3	2.1	4.0	25
	Barium	--	35.6	63.1	112	300	15
	Beryllium	--	--	--	--	<5.0	3
	Boron	--	19.5	31.5	51.0	160	42
	Cadmium	--	--	--	--	<10.0	24
	Chromium	--	--	--	--	<50.0	24
	Cobalt	<3.0	--	--	--	4.0	2
	Copper	--	0.74	2.4	7.9	80.0	26
	Iron	--	1.5	7.3	36.2	2,000	44
	Iron, unfiltered	--	35.0	45.0	235	740	8
	Lead	--	--	--	--	<50.0	23
	Lithium	12.0	--	--	--	--	1
	Manganese	--	0.10	0.68	4.8	130	31
	Mercury	--	--	--	--	<1.0	26
	Molybdenum	--	--	--	--	<100	2
	Nickel	--	--	--	--	<50.0	6
	Selenium	--	--	--	--	<10.0	28
	Strontium	150	--	--	--	--	1
	Vanadium	--	--	--	--	<100	2
	Zinc	--	11.0	26.0	53.0	1,500	23
	Gross alpha radioactivity (picocuries per liter)	--	1.0	1.5	3.3	4.6	4
	Gross beta radioactivity (picocuries per liter)	<1.0	--	4.2	--	8.0	3
	Radium-226 (picocuries per liter)	<0.20	--	--	--	0.20	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)—Continued	Radon-222, unfiltered (picocuries per liter)	540	620	740	1,000	1,500	11
	Uranium	1.0	--	--	--	35	2
Quaternary terrace-deposit aquifers (springs)	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	286	--	--	--	--	1
	Hardness (as $CaCO_3$)	139	--	--	--	--	1
	Calcium	43.0	--	--	--	--	1
	Magnesium	7.6	--	--	--	--	1
	Sodium	6.9	--	--	--	--	1
	Potassium	1.3	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.25	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	150	--	--	--	--	1
	Chloride	0.40	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	18.0	--	--	--	--	1
	Sulfate	5.0	--	--	--	--	1
	Total dissolved solids	173	--	--	--	--	1
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.16	--	--	--	--	1
	Nitrate (as N)	0.16	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Cadmium	10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	3.0	--	--	--	--	1
Quaternary terrace-deposit aquifers (wells)	Dissolved oxygen	0.10	0.20	2.3	6.8	8.1	14
	pH (standard units)	7.1	7.3	7.8	8.0	8.6	22
	Specific conductance (µS/cm)	114	253	286	386	493	22
	Hardness (as $CaCO_3$)	14.6	112	121	181	254	20
	Calcium	4.7	33.6	35.5	54.5	79.9	20
	Magnesium	0.69	6.4	8.0	10.5	13.1	20

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers (wells)—Continued	Sodium	2.1	6.1	7.2	8.2	94.0	20
	Potassium	0.60	1.9	2.0	2.3	2.5	20
	Sodium adsorption ratio (unitless)	0.12	0.24	0.25	0.28	10.7	20
	Alkalinity (as $CaCO_3$)	56.6	113	131	204	263	21
	Chloride	0.30	2.6	3.7	4.6	8.4	20
	Fluoride	0.10	0.33	0.39	0.40	0.50	18
	Silica	11.0	17.7	18.6	19.6	25.0	20
	Sulfate	2.0	6.1	8.5	11.2	42.0	20
	Total dissolved solids	58.0	154	178	235	267	20
	Ammonia (as N)	--	0.002	0.006	0.01	0.08	15
	Nitrate plus nitrite (as N)	--	0.03	0.14	0.64	1.4	16
	Nitrate (as N)	--	0.02	0.14	0.63	1.3	16
	Nitrite (as N)	--	0.0002	0.0006	0.002	0.006	15
	Organic nitrogen, unfiltered (as N)	--	--	--	--	<0.13	11
	Orthophosphate (as P)	--	0.01	0.02	0.02	0.03	15
	Phosphorus (as P)	0.02	--	--	--	--	1
	Phosphorus, unfiltered (as P)	--	0.01	0.01	0.02	0.03	11
	Dissolved organic carbon	--	0.30	0.50	0.70	0.70	11
	Boron	--	12.9	17.5	30.0	50.0	5
	Iron	--	1.9	8.5	135	592	16
	Manganese	--	0.13	21.3	967	1,690	13
	Radon-222, unfiltered (picocuries per liter)	700	--	--	--	--	1
Quaternary glacial-deposit aquifers (springs)	pH (standard units)	7.4	7.5	7.7	8.0	8.2	4
	Specific conductance (µS/cm)	125	203	384	488	489	4
	Hardness (as $CaCO_3$)	61.0	106	196	243	245	4
	Calcium	20.0	29.5	51.5	67.4	70.8	4
	Magnesium	2.8	7.9	14.3	18.3	21.0	4
	Sodium	1.6	1.9	5.0	9.8	11.8	4
	Potassium	0.90	--	1.4	--	4.4	3
	Sodium adsorption ratio (unitless)	0.07	0.09	0.16	0.27	0.33	4
	Alkalinity (as $CaCO_3$)	63.0	104	194	261	278	4
	Chloride	0.10	1.3	4.0	5.8	6.1	4
	Fluoride	0.10	--	0.20	--	0.40	3
	Silica	11.0	--	14.0	--	39.0	3
	Sulfate	1.6	2.5	4.1	9.0	13.0	4
	Total dissolved solids	78.0	123	232	304	312	4
	Nitrate plus nitrite (as N)	1.3	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers (springs)—Continued	Boron	<20.0	--	--	--	--	1
	Iron	--	--	--	--	<60.0	2
Quaternary glacial-deposit aquifers (wells)	Dissolved oxygen	0.20	3.7	6.9	8.5	10.8	10
	pH (standard units)	6.2	7.0	7.6	7.9	8.5	37
	Specific conductance (µS/cm)	32.0	134	225	470	627	37
	Hardness (as $CaCO_3$)	13.0	81.0	145	240	280	30
	Calcium	4.4	24.0	39.0	66.0	80.0	30
	Magnesium	0.50	4.3	9.9	17.0	25.0	30
	Sodium	0.90	3.5	5.9	14.0	52.6	30
	Potassium	0.60	1.3	2.5	3.1	6.2	30
	Sodium adsorption ratio (unitless)	0.01	0.15	0.20	0.48	1.7	30
	Alkalinity (as $CaCO_3$)	13.9	54.0	111	214	318	37
	Chloride	0.10	0.85	1.8	2.8	38.0	28
	Fluoride	0.10	0.17	0.20	0.40	0.80	25
	Silica	3.9	12.0	20.0	32.0	48.0	27
	Sulfate	0.40	1.9	5.7	12.0	90.0	30
	Total dissolved solids	18.0	128	176	301	378	30
	Ammonia (as N)	--	0.003	0.01	0.04	1.4	15
	Nitrate plus nitrite (as N)	--	0.06	0.10	0.18	0.71	21
	Nitrate (as N)	--	0.05	0.12	0.20	0.71	15
	Nitrite (as N)	--	--	--	--	<0.10	16
	Orthophosphate (as P)	--	0.004	0.01	0.03	0.19	15
	Phosphorus (as P)	0.01	--	0.01	--	0.03	3
	Dissolved organic carbon	0.20	--	--	--	0.60	2
	Aluminum	<10.0	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	2.0	2
	Barium	<100	--	--	--	--	1
	Beryllium	<1.0	--	--	--	--	1
	Boron	--	16.3	30.2	56.1	350	17
	Cadmium	--	--	--	--	<10.0	3
	Chromium	--	--	--	--	<50.0	2
	Copper	--	--	--	--	<10.0	2
	Iron	--	10.0	30.0	115	360	16
	Iron, unfiltered	--	30.0	40.0	160	1,480	13
	Lead	--	--	--	--	<10.0	2
	Manganese	--	1.4	10.0	63.0	520	7
	Mercury	--	--	--	--	<0.20	2
	Nickel	<20.0	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers (wells)—Continued	Selenium	--	--	--	--	<1.0	2
	Zinc	<10.0	--	--	--	1,250	3
	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)	230	--	--	--	7,200	2
	Uranium	<0.30	--	--	--	--	1
Quaternary landslide deposits (springs)	pH (standard units)	7.4	--	--	--	--	1
	Specific conductance (µS/cm)	311	--	--	--	--	1
	Hardness (as $CaCO_3$)	169	--	--	--	--	1
	Calcium	48.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	2.3	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.08	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	153	--	--	--	--	1
	Chloride	2.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	7.5	--	--	--	--	1
	Sulfate	14.0	--	--	--	--	1
	Total dissolved solids	179	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.11	--	--	--	--	1
	Nitrate (as N)	0.11	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
Quaternary loess and lithified talus deposits (wells)	pH (standard units)	7.7	7.9	8.1	8.2	8.2	4
	Specific conductance (µS/cm)	215	245	279	483	682	4
	Hardness (as $CaCO_3$)	110	124	139	245	349	4
	Calcium	34.0	34.5	37.0	60.5	82.0	4
	Magnesium	2.5	7.3	12.5	24.0	35.0	4
	Sodium	1.1	1.8	2.6	4.6	6.4	4
	Potassium	1.4	1.9	2.4	4.6	6.6	4

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary loess and lithified talus deposits (wells)—Continued	Sodium adsorption ratio (unitless)	0.05	0.07	0.09	0.12	0.15	4
	Alkalinity (as $CaCO_3$)	111	127	144	172	199	4
	Chloride	1.8	--	2.8	--	6.3	3
	Fluoride	0.10	0.15	0.20	0.55	0.90	4
	Silica	17.0	19.0	21.0	31.5	42.0	4
	Sulfate	3.3	--	4.2	--	170	3
	Total dissolved solids	130	146	165	319	469	4
	Ammonia (as N)	0.02	--	--	--	0.15	2
	Nitrate plus nitrite (as N)	0.05	--	--	--	0.14	2
	Nitrate (as N)	0.05	--	--	--	0.14	2
	Nitrite (as N)	0.01	--	--	--	0.01	2
	Orthophosphate (as P)	0.01	--	--	--	0.02	2
	Aluminum	10.0	--	--	--	--	1
	Arsenic	2.0	--	--	--	--	1
	Boron	<10.0	--	10.0	--	70.0	3
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	63.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	14.0	--	--	--	--	1
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks) (wells)	pH (standard units)	7.5	--	--	--	7.7	2
	Specific conductance (µS/cm)	472	--	--	--	490	2
	Hardness (as $CaCO_3$)	228	--	--	--	250	2
	Calcium	60.0	--	--	--	68.0	2
	Magnesium	18.0	--	--	--	19.0	2
	Sodium	9.1	--	--	--	9.5	2
	Potassium	1.9	--	--	--	3.0	2
	Sodium adsorption ratio (unitless)	0.25	--	--	--	0.27	2
	Alkalinity (as $CaCO_3$)	207	--	--	--	240	2
	Chloride	5.3	--	--	--	13.0	2
	Fluoride	0.30	--	--	--	0.30	2
	Silica	22.0	--	--	--	25.0	2
	Sulfate	9.9	--	--	--	24.0	2
	Total dissolved solids	275	--	--	--	288	2
	Ammonia (as N)	0.03	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks) (wells)—Continued	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.12	--	--	--	--	1
	Phosphorus (as P)	0.14	--	--	--	--	1
	Dissolved organic carbon	1.0	--	--	--	--	1
	Boron	60.0	--	--	--	--	1
	Iron	71.0	--	--	--	--	1
	Manganese	540	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	690	--	--	--	--	1
Miocene gravel deposits (wells)	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	146	--	--	--	--	1
	Hardness (as $CaCO_3$)	57.0	--	--	--	--	1
	Calcium	19.0	--	--	--	--	1
	Magnesium	2.5	--	--	--	--	1
	Sodium	5.9	--	--	--	--	1
	Potassium	1.9	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.30	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	63.0	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.30	--	--	--	--	1
	Silica	29.0	--	--	--	--	1
	Sulfate	3.3	--	--	--	--	1
	Total dissolved solids	102	--	--	--	--	1
	Nitrate (as N)	0.16	--	--	--	--	1
	Boron	<20.0	--	--	--	--	1
	Iron	<10.0	--	--	--	--	1
Camp Davis aquifer (springs)	pH (standard units)	7.4	--	7.7	--	8.0	3
	Specific conductance (µS/cm)	412	--	521	--	529	3
	Hardness (as $CaCO_3$)	199	--	--	--	--	1
	Calcium	53.0	--	66.0	--	71.0	3
	Magnesium	16.0	--	18.0	--	18.0	3
	Sodium	8.0	--	9.0	--	12.0	3
	Potassium	1.0	--	1.0	--	3.3	3
	Sodium adsorption ratio (unitless)	0.28	--	0.34	--	3.7	3
	Alkalinity (as $CaCO_3$)	197	--	233	--	246	3
	Chloride	3.8	--	5.5	--	12.8	3
	Fluoride	0.16	--	0.21	--	0.30	3

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Camp Davis aquifer (springs)—Continued	Silica	19.9	--	32.0	--	32.1	3
	Sulfate	4.9	--	13.0	--	14.7	3
	Total dissolved solids	252	--	288	--	292	3
	Ammonia (as N)	0.05	--	--	--	0.05	2
	Nitrate (as N)	1.1	--	--	--	1.6	2
	Nitrite (as N)	--	--	--	--	0.01	2
	Aluminum	<100	--	--	--	120	2
	Arsenic	<1.0	--	--	--	4.0	2
	Barium	180	--	--	--	230	2
	Boron	--	--	--	--	<100	3
	Cadmium	--	--	--	--	<10.0	2
	Chromium	--	--	--	--	<50.0	2
	Copper	--	--	--	--	<10.0	2
	Iron	<50.0	--	--	--	110	2
	Iron, unfiltered	30.0	--	--	--	--	1
	Lead	--	--	--	--	<50.0	2
	Manganese	<10.0	--	--	--	30.0	2
	Mercury	--	--	--	--	<1.0	2
	Molybdenum	--	--	--	--	<100	2
	Nickel	--	--	--	--	<50.0	2
	Selenium	--	--	--	--	<1.0	2
	Vanadium	--	--	--	--	<100	2
	Zinc	10.0	--	--	--	10.0	2
	Gross alpha radioactivity (picocuries per liter)	<1.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.70	--	--	--	--	1
Camp Davis aquifer (wells)	pH (standard units)	8.7	--	--	--	--	1
	Specific conductance (µS/cm)	312	--	--	--	--	1
	Calcium	5.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	62.0	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	7.6	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	113	--	--	--	--	1
	Chloride	8.5	--	--	--	--	1
	Fluoride	7.2	--	--	--	--	1
	Silica	14.8	--	--	--	--	1
	Sulfate	10.6	--	--	--	--	1
	Total dissolved solids	180	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Camp Davis aquifer (wells)—Continued	Ammonia (as N)	0.05	--	--	--	--	1
	Nitrate (as N)	0.40	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Aluminum	<100	--	--	--	--	1
	Arsenic	10.0	--	--	--	--	1
	Barium	<100	--	--	--	--	1
	Boron	<100	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	180	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Manganese	30.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Molybdenum	<100	--	--	--	--	1
	Nickel	<50.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Vanadium	<100	--	--	--	--	1
	Zinc	80.0	--	--	--	--	1
Teewinot aquifer (springs)	pH (standard units)	7.3	--	7.5	--	7.8	3
	Specific conductance (µS/cm)	371	--	376	--	380	3
	Hardness (as $CaCO_3$)	191	--	192	--	200	3
	Calcium	57.0	--	57.0	--	60.0	3
	Magnesium	12.0	--	12.0	--	13.0	3
	Sodium	2.3	--	2.3	--	2.5	3
	Potassium	3.5	--	3.9	--	5.1	3
	Sodium adsorption ratio (unitless)	0.07	--	0.08	--	0.10	3
	Alkalinity (as $CaCO_3$)	194	--	197	--	198	3
	Chloride	0.90	--	1.0	--	1.8	3
	Fluoride	0.40	--	0.40	--	0.50	3
	Silica	42.0	--	42.0	--	43.0	3
	Sulfate	2.5	--	5.8	--	6.2	3
	Total dissolved solids	244	--	247	--	254	3
	Ammonia (as N)	0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.04	--	--	--	0.11	2
	Nitrate (as N)	0.11	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Boron	10.0	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Teewinot aquifer (springs)—Continued	Iron	10.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
Teewinot aquifer (wells)	pH (standard units)	7.7	--	8.0	--	8.1	3
	Specific conductance (µS/cm)	253	--	316	--	395	3
	Hardness (as $CaCO_3$)	120	--	160	--	210	3
	Calcium	34.0	--	55.0	--	67.0	3
	Magnesium	4.6	--	8.6	--	10.0	3
	Sodium	2.7	--	3.7	--	3.7	3
	Potassium	3.4	--	3.7	--	4.0	3
	Sodium adsorption ratio (unitless)	0.10	--	0.11	--	0.11	3
	Alkalinity (as $CaCO_3$)	125	--	161	--	214	3
	Chloride	1.2	--	1.3	--	5.3	3
	Fluoride	0.30	--	0.30	--	0.50	3
	Silica	37.0	--	38.0	--	39.0	3
	Sulfate	1.6	--	2.6	--	3.3	3
	Total dissolved solids	166	--	212	--	260	3
	Ammonia (as N)	0.04	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.16	--	--	--	--	1
	Nitrate (as N)	0.05	--	--	--	0.16	2
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.04	--	--	--	--	1
	Boron	--	--	--	--	<20.0	2
	Iron	<10.0	--	--	--	20.0	2
Colter Formation (springs)	pH (standard units)	8.1	--	--	--	--	1
	Specific conductance (µS/cm)	177	--	--	--	--	1
	Hardness (as $CaCO_3$)	87.2	--	--	--	--	1
	Calcium	27.0	--	--	--	--	1
	Magnesium	4.8	--	--	--	--	1
	Sodium	2.1	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.10	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	91.0	--	--	--	--	1
	Chloride	0.80	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	21.0	--	--	--	--	1
	Sulfate	2.2	--	--	--	--	1
	Total dissolved solids	114	--	--	--	--	1
	Ammonia (as N)	0.03	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.07	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Colter Formation (springs)—Continued	Nitrate (as N)	0.07	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.03	--	--	--	--	1
	Aluminum	20.0	--	--	--	--	1
	Arsenic	4.0	--	--	--	--	1
	Boron	<10.0	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	1.0	--	--	--	--	1
	Iron	7.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	6.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	<3.0	--	--	--	--	1
Harebell Formation (springs)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	500	--	--	--	--	1
	Hardness (as $CaCO_3$)	250	--	--	--	--	1
	Calcium	79.0	--	--	--	--	1
	Magnesium	13.0	--	--	--	--	1
	Sodium	9.6	--	--	--	--	1
	Potassium	1.4	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.26	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	261	--	--	--	--	1
	Chloride	1.1	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	8.8	--	--	--	--	1
	Sulfate	5.8	--	--	--	--	1
	Total dissolved solids	278	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Iron	10.0	--	--	--	--	1
Harebell Formation (wells)	pH (standard units)	7.4	--	--	--	9.4	2
	Specific conductance (µS/cm)	474	--	--	--	524	2
	Hardness (as $CaCO_3$)	2.8	--	--	--	236	2
	Calcium	1.1	--	--	--	68.0	2
	Magnesium	0.02	--	--	--	16.0	2
	Sodium	22.0	--	--	--	110	2
	Potassium	0.20	--	--	--	3.2	2
	Sodium adsorption ratio (unitless)	0.62	--	--	--	28.5	2

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Harebell Formation (wells)—Continued	Alkalinity (as $CaCO_3$)	230	--	--	--	271	2
	Chloride	4.1	--	--	--	6.1	2
	Fluoride	0.20	--	--	--	8.2	2
	Silica	13.0	--	--	--	20.0	2
	Sulfate	2.4	--	--	--	15.0	2
	Total dissolved solids	280	--	--	--	314	2
	Ammonia (as N)	0.01	--	--	--	0.03	2
	Nitrate plus nitrite (as N)	0.05	--	--	--	0.53	2
	Nitrate (as N)	0.05	--	--	--	0.53	2
	Nitrite (as N)	0.01	--	--	--	0.01	2
	Orthophosphate (as P)	0.01	--	--	--	0.06	2
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	620	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	1.0	--	--	--	--	1
	Iron	53.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Manganese	1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	<3.0	--	--	--	--	1
Sohare Formation (wells)	pH (standard units)	8.4	--	--	--	--	1
	Specific conductance (µS/cm)	1,330	--	--	--	--	1
	Hardness (as $CaCO_3$)	24.8	--	--	--	--	1
	Calcium	5.8	--	--	--	--	1
	Magnesium	2.5	--	--	--	--	1
	Sodium	309	--	--	--	--	1
	Potassium	3.1	--	--	--	--	1
	Sodium adsorption ratio (unitless)	27.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	733	--	--	--	--	1
	Chloride	6.3	--	--	--	--	1
	Sulfate	1.0	--	--	--	--	1
	Total dissolved solids	866	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.10	--	--	--	--	1
	Iron	<50.0	--	--	--	--	1
	Iron, unfiltered	960	--	--	--	--	1
Bacon Ridge Sandstone (springs)	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	382	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bacon Ridge Sandstone (springs)—Continued	Hardness (as $CaCO_3$)	195	--	--	--	--	1
	Calcium	55.0	--	--	--	--	1
	Magnesium	14.0	--	--	--	--	1
	Sodium	6.3	--	--	--	--	1
	Potassium	1.3	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.20	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	188	--	--	--	--	1
	Chloride	0.10	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	7.9	--	--	--	--	1
	Sulfate	18.0	--	--	--	--	1
	Total dissolved solids	216	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.18	--	--	--	--	1
	Nitrate (as N)	0.18	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
Bacon Ridge Sandstone (wells)	pH (standard units)	9.2	--	--	--	--	1
	Specific conductance (µS/cm)	914	--	--	--	--	1
	Hardness (as $CaCO_3$)	4.6	--	--	--	--	1
	Calcium	1.3	--	--	--	--	1
	Magnesium	0.32	--	--	--	--	1
	Sodium	220	--	--	--	--	1
	Potassium	1.2	--	--	--	--	1
	Sodium adsorption ratio (unitless)	44.8	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	502	--	--	--	--	1
	Chloride	2.4	--	--	--	--	1
	Fluoride	1.6	--	--	--	--	1
	Silica	9.4	--	--	--	--	1
	Sulfate	9.7	--	--	--	--	1
	Total dissolved solids	547	--	--	--	--	1
	Ammonia (as N)	0.31	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.06	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aspen confining unit (wells)	Specific conductance (µS/cm)	501	--	--	--	533	2
	Hardness (as $CaCO_3$)	86.3	--	--	--	227	2
	Calcium	28.3	--	--	--	72.3	2
	Magnesium	3.8	--	--	--	11.2	2
	Sodium	21.7	--	--	--	71.6	2
	Sodium adsorption ratio (unitless)	0.63	--	--	--	3.4	2
	Fluoride	1.2	--	--	--	11.7	2
	Sulfate	4.9	--	--	--	10.5	2
	Total dissolved solids	284	--	--	--	312	2
	Nitrate (as N)	0.38	--	--	--	0.99	2
	Nitrite (as N)	<0.10	--	--	--	--	1
	Iron	100	--	--	--	540	2
Stump Formation (springs)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	465	--	--	--	--	1
	Calcium	67.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	8.0	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.24	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	226	--	--	--	--	1
	Chloride	2.7	--	--	--	--	1
	Fluoride	0.14	--	--	--	--	1
	Silica	17.1	--	--	--	--	1
	Sulfate	7.0	--	--	--	--	1
	Total dissolved solids	245	--	--	--	--	1
	Ammonia (as N)	0.05	--	--	--	--	1
	Nitrate (as N)	0.35	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Aluminum	<100	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Barium	290	--	--	--	--	1
	Boron	<100	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	<50.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Stump Formation (springs)—Continued	Molybdenum	<100	--	--	--	--	1
	Nickel	<50.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Vanadium	<100	--	--	--	--	1
	Zinc	10.0	--	--	--	--	1
Amsden aquifer (wells)	Dissolved oxygen	5.2	--	--	--	--	1
	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	541	--	--	--	--	1
	Hardness (as $CaCO_3$)	231	--	--	--	--	1
	Calcium	58.0	--	--	--	--	1
	Magnesium	21.0	--	--	--	--	1
	Sodium	27.0	--	--	--	--	1
	Potassium	2.6	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.77	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	201	--	--	--	--	1
	Chloride	18.0	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	59.0	--	--	--	--	1
	Total dissolved solids	327	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.67	--	--	--	--	1
	Nitrate (as N)	0.67	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Phosphorus (as P)	0.01	--	--	--	--	1
	Dissolved organic carbon	0.30	--	--	--	--	1
	Boron	230	--	--	--	--	1
	Iron	4.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	510	--	--	--	--	1
Madison aquifer (springs)	pH (standard units)	7.7	7.8	7.9	8.0	8.3	6
	Specific conductance (µS/cm)	237	348	422	480	850	6
	Hardness (as $CaCO_3$)	121	150	210	240	480	6
	Calcium	32.0	35.0	54.5	62.0	120	6
	Magnesium	10.0	17.0	18.5	21.0	44.0	6
	Sodium	0.90	3.2	5.1	7.2	7.6	6
	Potassium	0.40	1.6	1.7	2.6	2.7	6

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (springs)—Continued	Sodium adsorption ratio (unitless)	0.04	0.06	0.16	0.20	0.26	6
	Alkalinity (as $CaCO_3$)	122	144	148	171	190	6
	Chloride	1.8	2.2	2.3	2.4	2.9	6
	Fluoride	0.10	0.40	0.55	1.0	1.3	6
	Silica	4.5	9.8	11.0	13.0	14.0	6
	Sulfate	3.6	20.0	78.0	98.0	300	6
	Total dissolved solids	127	192	273	292	588	6
	Ammonia (as N)	0.04	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.06	--	--	--	0.11	2
	Nitrate (as N)	--	0.02	0.05	0.09	0.11	4
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Arsenic	<50.0	--	--	--	--	1
	Barium	<500	--	--	--	--	1
	Boron	--	20.0	25.0	65.0	100	4
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<100	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	10.0	--	10.0	--	20.0	3
	Iron, unfiltered	10.0	--	--	--	110	2
	Lead	<100	--	--	--	--	1
	Manganese	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Nickel	<100	--	--	--	--	1
	Selenium	2.0	--	--	--	--	1
	Zinc	<20.0	--	--	--	--	1
Madison aquifer (wells)	pH (standard units)	7.0	--	--	--	--	1
	Specific conductance (µS/cm)	431	--	--	--	--	1
	Hardness (as $CaCO_3$)	210	--	--	--	--	1
	Calcium	54.0	--	--	--	--	1
	Magnesium	19.0	--	--	--	--	1
	Sodium	6.4	--	--	--	--	1
	Potassium	2.1	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.20	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	144	--	--	--	--	1
	Chloride	2.0	--	--	--	--	1
	Fluoride	0.80	--	--	--	--	1
	Silica	16.0	--	--	--	--	1

Appendix E–3. Summary statistics for water samples, Jackson Hole, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (wells)—Continued	Sulfate	75.0	--	--	--	--	1
	Total dissolved solids	262	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.07	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Iron	10.0	--	--	--	--	1
Gallatin aquifer and confining unit (wells)	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	555	--	--	--	--	1
	Hardness (as $CaCO_3$)	300	--	--	--	--	1
	Calcium	74.0	--	--	--	--	1
	Magnesium	27.0	--	--	--	--	1
	Sodium	2.7	--	--	--	--	1
	Potassium	1.6	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.07	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	149	--	--	--	--	1
	Chloride	1.4	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	150	--	--	--	--	1
	Total dissolved solids	355	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Iron	10.0	--	--	--	--	1
Gros Ventre aquifer and confining unit (springs)	pH (standard units)	7.2	--	--	--	--	1
	Specific conductance (µS/cm)	530	--	--	--	--	1
	Hardness (as $CaCO_3$)	175	--	--	--	--	1
	Calcium	36.0	--	--	--	--	1
	Magnesium	21.0	--	--	--	--	1
	Sodium	50.0	--	--	--	--	1
	Potassium	5.3	--	--	--	--	1
	Sodium adsorption ratio (unitless)	1.6	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	205	--	--	--	--	1
	Chloride	23.0	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	15.0	--	--	--	--	1
	Sulfate	51.0	--	--	--	--	1
	Total dissolved solids	308	--	--	--	--	1
	Boron	140	--	--	--	--	1
	Iron, unfiltered	140	--	--	--	--	1

Appendix E-4

Statistics for water samples, Green and Hoback basins, Wyoming

Appendix E–4. Summary statistics for water samples, Green and Hoback River Basins, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (springs)	pH (standard units)	8.3	--	--	--	--	1
	Specific conductance (µS/cm)	415	--	--	--	--	1
	Hardness (as $CaCO_3$)	220	--	--	--	--	1
	Calcium	71.0	--	--	--	--	1
	Magnesium	9.9	--	--	--	--	1
	Sodium	2.1	--	--	--	--	1
	Potassium	0.70	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.06	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	143	--	--	--	--	1
	Chloride	1.5	--	--	--	--	1
	Fluoride	0.30	--	--	--	--	1
	Silica	5.8	--	--	--	--	1
	Sulfate	73.0	--	--	--	--	1
	Total dissolved solids	250	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
Quaternary alluvial aquifers (wells)	Dissolved oxygen	3.3	--	--	--	--	1
	pH (standard units)	6.8	7.6	7.8	8.0	8.0	8
	Specific conductance (µS/cm)	490	545	597	635	670	8
	Hardness (as $CaCO_3$)	260	260	290	320	334	7
	Calcium	82.0	83.0	95.0	105	110	7
	Magnesium	6.0	13.0	13.0	15.0	17.1	7
	Sodium	2.7	5.4	5.9	7.0	8.6	7
	Potassium	0.90	1.1	1.4	1.9	2.8	7
	Sodium adsorption ratio (unitless)	0.10	0.10	0.14	0.20	0.20	7
	Alkalinity (as $CaCO_3$)	138	151	201	229	244	7
	Chloride	0.40	1.1	1.4	2.4	2.4	7
	Fluoride	0.10	0.20	0.20	0.20	0.30	7
	Silica	4.6	5.6	6.6	7.4	7.5	7
	Sulfate	37.0	88.0	99.0	160	166	7
	Total dissolved solids	285	319	356	382	445	7
	Ammonia, unfiltered (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	--	0.05	0.07	0.13	0.14	7
	Nitrite (as N)	<0.02	--	--	--	--	1
	Organic nitrogen, unfiltered (as N)	<0.10	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Dissolved organic carbon	0.60	--	--	--	--	1
	Aluminum	<100	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1

Appendix E–4. Summary statistics for water samples, Green and Hoback River Basins, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)—Continued	Arsenic	<4.0	--	--	--	--	1
	Barium	32.9	--	--	--	--	1
	Beryllium	<1.0	--	--	--	--	1
	Boron	--	--	--	--	<100	7
	Cadmium	<0.20	--	--	--	--	1
	Chromium	<5.0	--	--	--	--	1
	Cobalt	2.0	--	--	--	--	1
	Copper	5.0	--	--	--	--	1
	Iron	--	--	--	--	<100	3
	Iron, unfiltered	--	8.6	20.0	30.0	170	6
	Lead	1.0	--	--	--	--	1
	Manganese	<2.0	--	--	--	--	1
	Manganese, unfiltered	<2.0	--	--	--	--	1
	Molybdenum	11.0	--	--	--	--	1
	Nickel	<4.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Strontium	1,040	--	--	--	--	1
	Vanadium	<10.0	--	--	--	--	1
	Zinc	<50.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	930	--	--	--	--	1
	Uranium	0.60	--	--	--	--	1
Quaternary glacial-deposit aquifers (springs)	Calcium	58.1	--	58.9	--	66.3	3
	Magnesium	10.6	--	10.8	--	17.4	3
	Sodium	1.2	--	1.3	--	2.0	3
	Potassium	0.39	--	0.43	--	0.59	3
	Sodium adsorption ratio (unitless)	0.04	--	0.04	--	0.06	3
	Alkalinity (as $CaCO_3$)	238	--	259	--	289	3
	Chloride	0.21	--	0.57	--	0.60	3
	Silica	1.6	--	2.6	--	3.2	3
	Sulfate	1.6	--	2.0	--	30.6	3
	Total dissolved solids	205	--	224	--	228	3
Quaternary landslide deposits (springs)	pH (standard units)	7.2	--	--	--	8.2	2
	Specific conductance (µS/cm)	165	--	--	--	--	1
	Hardness (as $CaCO_3$)	74.0	--	--	--	--	1
	Calcium	23.0	--	36.1	--	53.3	3
	Magnesium	4.0	--	7.3	--	12.3	3
	Sodium	0.46	--	1.3	--	4.3	3
	Potassium	0.08	--	0.27	--	0.50	3

Appendix E–4. Summary statistics for water samples, Green and Hoback River Basins, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary landslide deposits (springs)—Continued	Sodium adsorption ratio (unitless)	0.02	--	0.04	--	0.22	3
	Alkalinity (as $CaCO_3$)	67.2	--	170	--	199	3
	Chloride	0.14	--	0.71	--	4.9	3
	Fluoride	0.20	--	--	--	0.84	2
	Silica	1.3	--	1.8	--	3.6	3
	Sulfate	5.8	--	12.0	--	16.6	3
	Total dissolved solids	93.0	--	139	--	179	3
	Boron	50.0	--	--	--	--	1
Wasatch zone of the Wasatch-Fort Union aquifer (Pass Peak Formation) (springs)	pH (standard units)	8.2	--	--	--	8.2	2
	Specific conductance (µS/cm)	485	--	--	--	640	2
	Hardness (as $CaCO_3$)	250	--	--	--	320	2
	Calcium	71.0	--	--	--	86.0	2
	Magnesium	17.0	--	--	--	27.0	2
	Sodium	3.2	--	--	--	16.0	2
	Potassium	1.6	--	--	--	3.5	2
	Sodium adsorption ratio (unitless)	0.09	--	--	--	0.39	2
	Alkalinity (as $CaCO_3$)	217	--	--	--	328	2
	Chloride	1.8	--	--	--	1.8	2
	Fluoride	0.20	--	--	--	0.20	2
	Silica	8.7	--	--	--	13.0	2
	Sulfate	30.0	--	--	--	43.0	2
	Total dissolved solids	283	--	--	--	367	2
	Boron	20.0	--	--	--	20.0	2
	Iron	50.0	--	--	--	50.0	2
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation) (springs)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	387	--	--	--	--	1
	Hardness (as $CaCO_3$)	270	--	--	--	--	1
	Calcium	80.0	--	--	--	--	1
	Magnesium	17.0	--	--	--	--	1
	Sodium	2.8	--	--	--	--	1
	Potassium	0.60	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.07	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	267	--	--	--	--	1
	Chloride	3.9	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	5.9	--	--	--	--	1
	Sulfate	4.4	--	--	--	--	1
	Total dissolved solids	275	--	--	--	--	1

Appendix E–4. Summary statistics for water samples, Green and Hoback River Basins, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation) (springs)—Continued	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	<0.01	--	--	--	--	1
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Mercury	0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation) (wells)	pH (standard units)	7.3	--	--	--	7.9	2
	Specific conductance (µS/cm)	379	--	--	--	550	2
	Hardness (as $CaCO_3$)	199	--	--	--	270	2
	Calcium	50.0	--	--	--	89.0	2
	Magnesium	12.0	--	--	--	18.0	2
	Sodium	5.6	--	--	--	7.0	2
	Potassium	1.2	--	--	--	1.4	2
	Sodium adsorption ratio (unitless)	0.17	--	--	--	0.20	2
	Alkalinity (as $CaCO_3$)	185	--	--	--	190	2
	Chloride	1.8	--	--	--	3.3	2
	Fluoride	0.20	--	--	--	0.20	2
	Silica	6.0	--	--	--	8.2	2
	Sulfate	15.0	--	--	--	99.0	2
	Total dissolved solids	215	--	--	--	327	2
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
	Aluminum	<10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	--	--	--	--	<20	2
	Chromium	<1.0	--	--	--	--	1
	Copper	<1.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1

Appendix E–4. Summary statistics for water samples, Green and Hoback River Basins, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation) (wells)—Continued	Iron, unfiltered	20.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Tensleep aquifer (springs)	pH (standard units)	8.0	--	--	--	--	1
	Calcium	71.3	--	--	--	--	1
	Magnesium	25.5	--	--	--	--	1
	Sodium	2.1	--	--	--	--	1
	Potassium	0.08	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.05	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	211	--	--	--	--	1
	Chloride	0.35	--	--	--	--	1
	Fluoride	0.84	--	--	--	--	1
	Silica	1.7	--	--	--	--	1
	Sulfate	99.9	--	--	--	--	1
	Total dissolved solids	303	--	--	--	--	1
Madison aquifer (springs)	Calcium	26.7	--	--	--	27.1	2
	Magnesium	5.7	--	--	--	6.9	2
	Sodium	0.18	--	--	--	0.39	2
	Potassium	0.20	--	--	--	0.31	2
	Sodium adsorption ratio (unitless)	0.008	--	--	--	0.02	2
	Alkalinity (as $CaCO_3$)	111	--	--	--	115	2
	Chloride	0.25	--	--	--	0.28	2
	Silica	1.1	--	--	--	1.6	2
	Sulfate	5.9	--	--	--	9.1	2
	Total dissolved solids	94.6	--	--	--	102	2

Appendix E-5

Statistics for water samples, Overthrust Belt, Wyoming

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)	pH (standard units)	7.4	7.6	7.6	7.7	7.8	8
	Specific conductance (µS/cm)	419	436	529	560	567	7
	Hardness (as $CaCO_3$)	215	250	257	270	290	6
	Calcium	52.0	64.0	68.0	83.0	83.0	7
	Magnesium	11.0	15.0	19.0	21.0	25.0	7
	Sodium	2.5	2.8	6.7	12.0	18.0	7
	Potassium	0.70	0.80	1.0	3.0	17.0	7
	Sodium adsorption ratio (unitless)	0.08	0.10	0.20	0.30	0.49	7
	Alkalinity (as $CaCO_3$)	180	191	219	238	255	7
	Chloride	0.80	1.0	1.6	13.0	20.0	7
	Fluoride	0.10	0.10	0.20	0.30	0.60	6
	Silica	6.6	7.9	9.9	12.0	13.0	6
	Sulfate	33.0	36.0	48.0	75.0	82.0	7
	Total dissolved solids	230	254	311	315	333	7
	Ammonia (as N)	<0.01	--	--	--	0.02	3
	Nitrate plus nitrite (as N)	--	0.43	0.54	0.70	0.98	6
	Nitrate (as N)	0.16	--	0.43	--	0.60	3
	Nitrite (as N)	--	--	--	--	<0.01	3
	Orthophosphate (as P)	0.02	--	0.02	--	0.02	3
	Boron	--	20.0	20.0	20.0	40.0	5
	Iron	<3.0	--	--	--	10.0	2
	Iron, unfiltered	10.0	--	50.0	--	60.0	3
	Manganese	--	--	--	--	<1.0	2
	Radon-222, unfiltered (picocuries per liter)	1,580	--	--	--	--	1
Quaternary terrace-deposit aquifers (springs)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	419	--	--	--	--	1
	Hardness (as $CaCO_3$)	212	--	--	--	--	1
	Calcium	60.0	--	--	--	--	1
	Magnesium	15.0	--	--	--	--	1
	Sodium	3.8	--	--	--	--	1
	Potassium	0.70	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.11	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	217	--	--	--	--	1
	Chloride	1.2	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	9.1	--	--	--	--	1
	Total dissolved solids	231	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers (springs)	pH (standard units)	7.5	--	8.0	--	8.2	3
	Specific conductance (µS/cm)	254	--	319	--	391	3
	Hardness (as $CaCO_3$)	118	--	--	--	198	2
	Calcium	36.0	--	--	--	71.0	2
	Magnesium	5.0	--	--	--	6.9	2
	Sodium	2.1	--	--	--	2.5	2
	Potassium	0.30	--	--	--	0.60	2
	Sodium adsorption ratio (unitless)	0.08	--	--	--	0.08	2
	Alkalinity (as $CaCO_3$)	68.0	--	--	--	209	2
	Chloride	0.20	--	--	--	0.50	2
	Fluoride	0.10	--	--	--	0.20	2
	Silica	8.8	--	--	--	9.0	2
	Sulfate	2.7	--	--	--	54.0	2
	Total dissolved solids	149	--	--	--	215	2
Quaternary landslide deposits (springs)	pH (standard units)	7.0	--	--	--	--	1
	Specific conductance (µS/cm)	403	--	--	--	--	1
	Hardness (as $CaCO_3$)	202	--	--	--	--	1
	Calcium	67.0	--	--	--	--	1
	Magnesium	8.5	--	--	--	--	1
	Sodium	4.9	--	--	--	--	1
	Potassium	1.4	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.15	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	194	--	--	--	--	1
	Chloride	4.1	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	9.4	--	--	--	--	1
	Sulfate	22.0	--	--	--	--	1
	Total dissolved solids	234	--	--	--	--	1
	Ammonia (as N)	0.05	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.11	--	--	--	--	1
	Nitrate (as N)	0.11	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.03	--	--	--	--	1
Salt Lake aquifer (springs)	pH (standard units)	7.3	--	--	--	8.1	2
	Specific conductance (µS/cm)	346	--	--	--	360	2
	Hardness (as $CaCO_3$)	189	--	--	--	200	2
	Calcium	41.0	--	--	--	64.0	2
	Magnesium	7.0	--	--	--	24.0	2
	Sodium	1.6	--	--	--	3.0	2

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Salt Lake aquifer (springs)—Continued	Potassium	0.60	--	--	--	1.0	2
	Sodium adsorption ratio (unitless)	0.10	--	--	--	0.10	2
	Alkalinity (as $CaCO_3$)	167	--	--	--	203	2
	Chloride	0.70	--	--	--	1.0	2
	Fluoride	0.10	--	--	--	0.10	2
	Silica	7.9	--	--	--	--	1
	Sulfate	3.8	--	--	--	17.0	2
	Total dissolved solids	193	--	--	--	202	2
	Ammonia (as N)	<0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.10	--	--	--	0.26	2
	Phosphorus, unfiltered (as P)	0.04	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
Camp Davis aquifer (wells)	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	511	--	--	--	--	1
	Hardness (as $CaCO_3$)	280	--	--	--	--	1
	Calcium	96.0	--	--	--	--	1
	Magnesium	9.7	--	--	--	--	1
	Sodium	4.8	--	--	--	--	1
	Potassium	1.9	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.12	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	250	--	--	--	--	1
	Chloride	9.8	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	14.0	--	--	--	--	1
	Sulfate	17.0	--	--	--	--	1
	Total dissolved solids	306	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.58	--	--	--	--	1
	Nitrate (as N)	0.58	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.15	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Chromium	<1.0	--	--	--	--	1
	Copper	2.0	--	--	--	--	1
	Lead	<1.0	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Camp Davis aquifer (wells)—Continued	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Blind Bull Formation (springs)	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	303	--	--	--	--	1
	Hardness (as $CaCO_3$)	140	--	--	--	--	1
	Calcium	37.0	--	--	--	--	1
	Magnesium	11.0	--	--	--	--	1
	Sodium	9.3	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.30	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	141	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	5.7	--	--	--	--	1
	Sulfate	21.0	--	--	--	--	1
	Total dissolved solids	172	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.16	--	--	--	--	1
	Boron	50.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
Aspen confining unit (springs)	pH (standard units)	7.5	7.6	7.8	8.1	8.5	9
	Specific conductance (µS/cm)	317	326	336	359	390	7
	Hardness (as $CaCO_3$)	130	135	145	167	184	4
	Calcium	31.0	45.0	50.9	54.0	62.0	6
	Magnesium	4.1	4.6	5.9	7.1	11.0	6
	Sodium	0.62	0.64	10.9	14.0	21.0	6
	Potassium	0.23	0.23	1.5	1.6	1.6	6
	Sodium adsorption ratio (unitless)	0.02	0.03	0.39	0.50	0.80	6
	Alkalinity (as $CaCO_3$)	107	167	174	180	195	6
	Chloride	0.25	0.25	1.0	1.4	3.1	6
	Fluoride	0.30	0.30	0.30	0.65	1.0	4
	Silica	2.3	2.4	9.1	12.0	17.0	6
	Sulfate	1.2	1.4	7.9	14.0	17.0	6
	Total dissolved solids	107	173	195	212	228	6
	Nitrate plus nitrite (as N)	0.06	--	0.14	--	0.17	3
	Nitrate (as N)	0.60	--	--	--	--	1
	Boron	20.0	--	30.0	--	60.0	3
	Iron, unfiltered	10.0	--	10.0	--	40.0	3

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aspen confining unit (wells)	pH (standard units)	7.4	--	--	--	--	1
	Specific conductance (µS/cm)	515	--	--	--	--	1
	Hardness (as $CaCO_3$)	268	--	--	--	--	1
	Calcium	76.0	--	--	--	--	1
	Magnesium	19.0	--	--	--	--	1
	Sodium	11.0	--	--	--	--	1
	Potassium	0.70	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.29	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	271	--	--	--	--	1
	Chloride	6.6	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	9.4	--	--	--	--	1
	Total dissolved solids	308	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.79	--	--	--	--	1
	Nitrate (as N)	0.79	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.03	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
	Aluminum	10.0	--	--	--	--	1
	Arsenic	1.0	--	--	--	--	1
	Boron	20.0	--	--	--	--	1
	Chromium	1.0	--	--	--	--	1
	Copper	2.0	--	--	--	--	1
	Lead	1.0	--	--	--	--	1
	Mercury	<0.10	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
Bear River aquifer (springs)	pH (standard units)	7.8	7.9	8.0	8.1	8.2	4
	Specific conductance (µS/cm)	402	413	435	452	457	4
	Hardness (as $CaCO_3$)	213	214	227	248	256	4
	Calcium	64.0	65.0	66.0	71.0	76.0	4
	Magnesium	12.0	12.5	14.5	17.0	18.0	4
	Sodium	1.0	2.3	5.4	8.1	9.0	4
	Potassium	0.40	0.65	1.3	1.6	1.6	4
	Sodium adsorption ratio (unitless)	0.03	0.07	0.15	0.24	0.27	4
	Alkalinity (as $CaCO_3$)	202	206	225	241	243	4
	Chloride	2.1	2.6	3.1	4.2	5.2	4
	Fluoride	0.20	0.20	0.25	0.30	0.30	4

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bear River aquifer (springs)—Continued	Silica	7.5	7.7	7.9	8.4	8.8	4
	Sulfate	3.3	4.1	7.0	12.5	16.0	4
	Total dissolved solids	226	234	248	259	264	4
	Nitrate (as N)	0.40	--	0.40	--	0.50	3
Bear River aquifer (wells)	pH (standard units)	6.7	7.5	7.7	8.1	8.9	8
	Specific conductance (µS/cm)	328	462	869	1,380	1,710	8
	Hardness (as $CaCO_3$)	4.9	161	201	350	445	6
	Calcium	1.1	54.0	64.5	120	172	8
	Magnesium	0.51	6.8	13.5	24.0	37.0	8
	Sodium	7.9	16.1	36.0	125	410	8
	Potassium	0.70	1.6	2.1	2.9	7.0	8
	Sodium adsorption ratio (unitless)	0.20	0.54	0.90	3.1	81.0	8
	Alkalinity (as $CaCO_3$)	175	220	317	401	699	8
	Chloride	1.3	4.2	12.0	101	319	8
	Fluoride	0.10	0.20	0.73	1.9	3.3	7
	Silica	7.2	12.0	13.0	17.0	19.0	7
	Sulfate	3.0	14.1	24.5	27.5	210	8
	Total dissolved solids	197	250	504	884	1,120	8
	Ammonia (as N)	<0.01	--	0.12	--	0.17	3
	Nitrate plus nitrite (as N)	--	3.8	7.8	8.9	9.7	4
	Nitrate (as N)	--	0.28	2.8	7.2	9.7	5
	Nitrite (as N)	<0.01	--	--	--	0.27	4
	Orthophosphate (as P)	0.01	--	0.04	--	0.04	3
	Phosphorus, unfiltered (as P)	0.01	--	--	--	0.12	2
	Aluminum	<10.0	--	--	--	10.0	3
	Arsenic	<1.0	--	--	--	1.0	4
	Barium	100	--	--	--	400	2
	Beryllium	--	--	--	--	<0.05	2
	Boron	--	50.0	60.0	120	410	5
	Cadmium	--	--	--	--	<10.0	3
	Chromium	--	--	--	--	<1.0	3
	Cobalt	--	--	--	--	<3.0	2
	Copper	<1.0	--	7.0	--	9.0	3
	Iron	16.0	--	28.0	--	54.0	3
	Iron, unfiltered	10.0	--	--	--	30.0	2
	Lead	--	--	--	--	<1.0	3
	Lithium	23.0	--	--	--	37.0	2
	Manganese	1.0	--	2.0	--	4.0	3
	Mercury	--	--	--	--	<0.10	3

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bear River aquifer (wells)—Continued	Selenium	<1.0	--	--	--	2.0	3
	Strontium	220	--	--	--	430	2
	Zinc	5.0	--	26.0	--	260	3
Gannett aquifer and confining unit (springs)	pH (standard units)	7.4	--	7.6	--	8.0	3
	Specific conductance (µS/cm)	241	--	352	--	407	3
	Hardness (as $CaCO_3$)	100	--	180	--	200	3
	Calcium	29.0	--	48.0	--	57.0	3
	Magnesium	7.8	--	8.8	--	19.0	3
	Sodium	5.1	--	8.2	--	10.0	3
	Potassium	0.70	--	0.80	--	1.0	3
	Sodium adsorption ratio (unitless)	0.20	--	0.30	--	0.40	3
	Alkalinity (as $CaCO_3$)	107	--	194	--	220	3
	Chloride	1.4	--	1.7	--	2.1	3
	Fluoride	0.10	--	--	--	0.20	2
	Silica	7.6	--	9.2	--	12.0	3
	Sulfate	4.0	--	7.1	--	21.0	3
	Total dissolved solids	141	--	208	--	228	3
	Nitrate plus nitrite (as N)	0.04	--	0.19	--	0.32	3
	Boron	20.0	--	40.0	--	40.0	3
	Iron, unfiltered	20.0	--	--	--	20.0	2
Gannett aquifer and confining unit (wells)	pH (standard units)	8.6	--	--	--	--	1
	Specific conductance (µS/cm)	390	--	--	--	--	1
	Hardness (as $CaCO_3$)	264	--	--	--	--	1
	Calcium	86.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	8.0	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.21	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	248	--	--	--	--	1
	Chloride	11.0	--	--	--	--	1
	Fluoride	0.26	--	--	--	--	1
	Sulfate	16.0	--	--	--	--	1
	Total dissolved solids	318	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.28	--	--	--	--	1
	Nitrate (as N)	4.9	--	--	--	--	1
	Arsenic	<10.0	--	--	--	--	1
	Barium	220	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Gannett aquifer and confining unit (wells)—Continued	Chromium	<50.0	--	--	--	--	1
	Iron, unfiltered	10.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Selenium	<10.0	--	--	--	--	1
	Uranium	<1.0	--	--	--	--	1
Stump Formation (springs)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	442	--	--	--	--	1
	Hardness (as $CaCO_3$)	229	--	--	--	--	1
	Calcium	67.0	--	--	--	--	1
	Magnesium	15.0	--	--	--	--	1
	Sodium	3.0	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.09	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	221	--	--	--	--	1
	Chloride	0.80	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	9.1	--	--	--	--	1
	Sulfate	4.4	--	--	--	--	1
	Total dissolved solids	241	--	--	--	--	1
Twin Creek aquifer (springs)	pH (standard units)	7.4	7.6	7.8	7.8	7.9	6
	Specific conductance (µS/cm)	230	275	350	421	526	9
	Hardness (as $CaCO_3$)	109	169	196	250	280	7
	Calcium	24.0	51.0	57.9	80.0	82.0	7
	Magnesium	0.75	9.2	13.0	17.0	18.0	7
	Sodium	1.6	2.0	3.0	4.3	5.7	7
	Potassium	0.50	0.70	0.70	1.0	1.0	6
	Sodium adsorption ratio (unitless)	0.06	0.06	0.09	0.10	0.24	7
	Alkalinity (as $CaCO_3$)	104	138	184	230	257	7
	Chloride	0.21	0.45	1.0	1.9	3.1	10
	Fluoride	0.09	0.10	0.10	0.10	0.20	9
	Silica	8.6	--	9.5	--	12.0	3
	Sulfate	5.1	13.0	19.0	37.0	67.0	10
	Total dissolved solids	133	174	219	282	326	7
	Ammonia (as N)	--	--	--	--	<0.10	3
	Nitrate plus nitrite (as N)	--	0.10	0.13	0.15	0.19	5
	Nitrate (as N)	0.39	--	--	--	--	1
	Phosphorus (as P)	0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	0.01	2

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Twin Creek aquifer (springs)—Continued	Arsenic	--	--	--	--	<2.0	4
	Barium	<100	--	--	--	--	1
	Boron	40.0	--	--	--	--	1
	Cadmium	1.0	--	--	--	--	1
	Chromium	<5.0	--	--	--	--	1
	Copper	--	3.2	3.8	4.5	5.7	6
	Iron	--	--	--	--	<30.0	4
	Iron, unfiltered	10.0	--	--	--	--	1
	Lead	--	--	--	--	<50.0	4
	Manganese	--	--	--	--	<10.0	4
	Mercury	<0.20	--	--	--	--	1
	Molybdenum	<1.0	--	1.5	--	2.2	3
	Selenium	<1.0	--	--	--	--	1
	Zinc	--	5.0	5.8	6.6	7.0	6
	Gross alpha radioactivity (picocuries per liter)	2.6	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	1.5	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	4.4	--	--	--	--	1
	Uranium	0.18	--	0.20	--	0.20	3
Nugget aquifer (springs)	pH (standard units)	6.8	7.6	7.7	8.0	8.3	10
	Specific conductance (µS/cm)	178	185	243	253	605	5
	Hardness (as $CaCO_3$)	90.5	91.9	112	224	317	4
	Calcium	5.8	23.6	29.0	38.1	89.0	9
	Magnesium	1.8	4.4	6.6	7.5	23.0	9
	Sodium	0.99	1.2	1.4	1.5	2.1	9
	Potassium	0.27	0.31	0.40	0.90	4.4	9
	Sodium adsorption ratio (unitless)	0.04	0.05	0.06	0.07	0.09	9
	Alkalinity (as $CaCO_3$)	21.7	79.6	87.7	117	125	9
	Chloride	0.21	0.46	0.57	1.7	2.1	9
	Fluoride	0.10	0.15	0.20	0.25	0.30	4
	Silica	2.4	2.8	3.8	8.0	10.0	9
	Sulfate	1.0	1.8	3.8	4.9	190	9
	Total dissolved solids	30.0	85.0	106	134	388	9
	Nitrate (as N)	0.07	--	--	--	0.60	2
Nugget aquifer (wells)	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	465	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Nugget aquifer (wells)—Continued	Hardness (as $CaCO_3$)	236	--	--	--	--	1
	Calcium	50.0	--	--	--	--	1
	Magnesium	27.0	--	--	--	--	1
	Sodium	3.6	--	--	--	--	1
	Potassium	1.3	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.10	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	177	--	--	--	--	1
	Chloride	2.5	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	10.0	--	--	--	--	1
	Sulfate	69.0	--	--	--	--	1
	Total dissolved solids	269	--	--	--	--	1
	Ammonia (as N)	0.02	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	<0.01	--	--	--	--	1
Ankareh aquifer (springs)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	533	--	--	--	--	1
	Hardness (as $CaCO_3$)	231	--	--	--	235	2
	Calcium	59.0	--	--	--	73.8	2
	Magnesium	0.92	--	--	--	21.0	2
	Sodium	1.6	--	--	--	7.0	2
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.05	--	--	--	0.20	2
	Alkalinity (as $CaCO_3$)	170	--	--	--	214	2
	Chloride	1.3	--	--	--	25.0	2
	Fluoride	0.10	--	--	--	0.10	2
	Sulfate	28.5	--	--	--	47.0	2
	Total dissolved solids	263	--	--	--	364	2
	Ammonia (as N)	<0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.26	--	--	--	--	1
	Nitrate (as N)	0.22	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Barium	<100	--	--	--	--	1
	Cadmium	1.0	--	--	--	--	1
	Chromium	<5.0	--	--	--	--	1
	Iron	30.0	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Ankareh aquifer (springs)—Continued	Lead	<5.0	--	--	--	--	1
	Manganese	7.0	--	--	--	--	1
	Mercury	<0.20	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	<1.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	1.9	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	1.9	--	--	--	--	1
Thaynes aquifer (springs)	pH (standard units)	7.4	7.7	7.9	8.0	8.2	6
	Specific conductance (µS/cm)	364	--	--	--	--	1
	Hardness (as $CaCO_3$)	206	--	--	--	--	1
	Calcium	23.3	35.4	46.0	49.7	52.0	6
	Magnesium	6.9	12.1	12.7	13.8	19.0	6
	Sodium	0.53	0.90	0.97	1.7	2.0	6
	Potassium	0.23	0.27	0.99	2.6	4.2	6
	Sodium adsorption ratio (unitless)	0.02	0.03	0.03	0.06	0.06	6
	Alkalinity (as $CaCO_3$)	89.3	114	130	152	153	6
	Chloride	0.07	0.25	0.27	0.39	1.0	6
	Fluoride	0.20	--	--	--	--	1
	Silica	1.4	2.1	2.1	2.9	3.0	5
	Sulfate	2.4	11.5	27.8	53.9	57.0	6
	Total dissolved solids	89.0	146	186	200	281	6
	Ammonia (as N)	<0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.18	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
	Arsenic	2.0	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	<30.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Zinc	<10.0	--	--	--	--	1
Woodside confining unit (springs)	Specific conductance (µS/cm)	230	--	--	--	460	2
	Chloride	0.49	--	--	--	0.51	2
	Fluoride	0.24	--	--	--	0.40	2
	Sulfate	3.2	--	--	--	85.0	2
	Copper	4.0	--	--	--	--	1
	Molybdenum	1.0	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Woodside confining unit (springs)—Continued	Zinc	2.0	--	--	--	--	1
	Uranium	0.22	--	--	--	0.44	2
Phosphoria aquifer (springs)	Specific conductance (µS/cm)	320	--	--	--	--	1
	Chloride	0.19	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Sulfate	39.0	--	--	--	--	1
	Copper	3.7	--	--	--	--	1
	Molybdenum	2.0	--	--	--	--	1
	Zinc	8.0	--	--	--	--	1
	Uranium	0.56	--	--	--	--	1
Wells aquifer (springs)	pH (standard units)	6.6	7.7	7.7	7.9	8.0	10
	Specific conductance (µS/cm)	220	240	287	310	411	6
	Hardness (as $CaCO_3$)	140	153	168	200	230	4
	Calcium	26.2	39.2	42.9	46.0	61.4	10
	Magnesium	9.2	11.3	13.7	16.4	26.0	10
	Sodium	0.30	0.80	0.90	0.99	1.7	10
	Potassium	0.30	0.30	0.94	2.7	2.8	10
	Sodium adsorption ratio (unitless)	0.01	0.01	0.03	0.03	0.03	10
	Alkalinity (as $CaCO_3$)	104	135	160	178	223	10
	Chloride	0.31	0.39	0.44	0.95	2.1	12
	Fluoride	0.10	0.12	0.20	0.30	0.40	5
	Silica	2.2	2.5	2.9	4.5	6.9	10
	Sulfate	1.2	3.2	7.7	11.2	22.9	12
	Total dissolved solids	114	143	171	193	239	10
	Nitrate plus nitrite (as N)	0.25	--	0.38	--	0.51	3
	Nitrate (as N)	0.27	--	--	--	--	1
	Boron	10.0	--	--	--	20.0	2
	Copper	2.1	--	--	--	2.8	2
	Iron	10.0	--	--	--	--	1
	Iron, unfiltered	10.0	--	--	--	10.0	2
	Molybdenum	<1.0	--	--	--	2.5	2
	Zinc	3.0	--	--	--	14.0	2
	Uranium	0.20	--	--	--	0.40	2
Wells aquifer (wells)	pH (standard units)	7.8	--	--	--	--	1
	Calcium	59.5	--	--	--	--	1
	Magnesium	22.0	--	--	--	--	1
	Sodium	3.2	--	--	--	--	1
	Potassium	2.6	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.09	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wells aquifer (wells)—Continued	Alkalinity (as $CaCO_3$)	210	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.76	--	--	--	--	1
	Sulfate	91.7	--	--	--	--	1
	Total dissolved solids	317	--	--	--	--	1
	Nitrate (as N)	0.27	--	--	--	--	1
Amsden aquifer (springs)	pH (standard units)	7.9	--	7.9	--	8.2	3
	Calcium	28.9	--	33.2	--	41.7	3
	Magnesium	11.4	--	12.8	--	14.0	3
	Sodium	0.46	--	0.53	--	0.69	3
	Potassium	0.23	--	0.39	--	0.39	3
	Sodium adsorption ratio (unitless)	0.02	--	0.02	--	0.03	3
	Alkalinity (as $CaCO_3$)	122	--	140	--	145	3
	Chloride	0.28	--	0.39	--	0.46	3
	Silica	2.3	--	--	--	2.4	2
	Sulfate	1.9	--	2.9	--	33.3	3
	Total dissolved solids	119	--	138	--	178	3
Madison aquifer (hot springs)	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	1,550	--	--	--	--	1
	Hardness (as $CaCO_3$)	590	--	--	--	--	1
	Calcium	170	--	--	--	--	1
	Magnesium	43.0	--	--	--	--	1
	Sodium	120	--	--	--	--	1
	Potassium	13.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	2.1	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	300	--	--	--	--	1
	Chloride	97.0	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	26.0	--	--	--	--	1
	Sulfate	520	--	--	--	--	1
	Total dissolved solids	1,160	--	--	--	--	1
	Arsenic	<50.0	--	--	--	--	1
	Barium	<500	--	--	--	--	1
	Boron	170	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<100	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Lead	<100	--	--	--	--	1
	Manganese	<50.0	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (hot springs)—Continued	Mercury	<1.0	--	--	--	--	1
	Nickel	<100	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	330	--	--	--	--	1
Madison aquifer (springs)	pH (standard units)	7.7	7.8	7.9	8.0	8.3	18
	Specific conductance (µS/cm)	195	--	338	--	511	3
	Hardness (as $CaCO_3$)	97.8	146	149	170	266	5
	Calcium	24.4	38.4	48.2	67.0	79.9	18
	Magnesium	6.8	12.7	14.6	19.3	24.0	18
	Sodium	0.23	0.55	0.62	0.80	1.4	18
	Potassium	0.20	0.47	0.57	0.78	3.9	18
	Sodium adsorption ratio (unitless)	0.01	0.02	0.02	0.02	0.05	18
	Alkalinity (as $CaCO_3$)	77.6	128	132	150	191	18
	Chloride	0.07	0.25	0.30	0.50	1.1	18
	Fluoride	0.30	--	0.40	--	0.40	3
	Silica	1.3	2.5	2.6	4.0	5.6	9
	Sulfate	4.8	7.0	21.7	79.2	132	18
	Total dissolved solids	89.0	136	194	253	319	18
	Ammonia (as N)	--	--	--	--	<0.10	2
	Nitrate plus nitrite (as N)	0.15	--	--	--	0.19	2
	Nitrate (as N)	<1.0	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	0.02	2
	Arsenic	<2.0	--	--	--	3.0	2
	Barium	<300	--	--	--	--	1
	Boron	10.0	--	--	--	--	1
	Cadmium	<2.0	--	--	--	--	1
	Chromium	<4.0	--	--	--	--	1
	Copper	--	--	--	--	<10.0	2
	Iron	--	--	--	--	<30.0	2
	Iron, unfiltered	20.0	--	--	--	--	1
	Lead	--	--	--	--	<50.0	2
	Manganese	--	--	--	--	<10.0	2
	Mercury	<0.20	--	--	--	--	1
	Nickel	<20.0	--	--	--	--	1
	Selenium	<2.0	--	--	--	--	1
	Zinc	20.0	--	--	--	25.0	2
Madison aquifer (wells)	pH (standard units)	7.5	--	--	--	8.5	2
	Specific conductance (µS/cm)	310	--	--	--	1,630	2
	Hardness (as $CaCO_3$)	158	--	--	--	640	2
	Calcium	50.0	--	--	--	180	2

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (wells)—Continued	Magnesium	8.0	--	--	--	46.0	2
	Sodium	10.0	--	--	--	110	2
	Potassium	2.0	--	--	--	14.0	2
	Sodium adsorption ratio (unitless)	0.35	--	--	--	1.9	2
	Alkalinity (as $CaCO_3$)	179	--	--	--	253	2
	Chloride	7.0	--	--	--	90.0	2
	Fluoride	0.40	--	--	--	0.44	2
	Silica	27.0	--	--	--	--	1
	Sulfate	7.0	--	--	--	530	2
	Total dissolved solids	110	--	--	--	1,150	2
	Nitrate plus nitrite (as N)	0.04	--	--	--	--	1
	Nitrate (as N)	<0.01	--	--	--	--	1
	Arsenic	<10.0	--	--	--	--	1
	Barium	80.0	--	--	--	--	1
	Boron	230	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Iron, unfiltered	5,000	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Selenium	<10.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	4.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	1.0	--	--	--	--	1
	Uranium	<1.0	--	--	--	--	1
Darby aquifer (springs)	Dissolved oxygen	1.8	--	--	--	--	1
	pH (standard units)	7.2	7.4	7.6	7.9	8.1	4
	Specific conductance (µS/cm)	389	--	1,520	--	1,580	3
	Hardness (as $CaCO_3$)	206	--	870	--	1,100	3
	Calcium	35.1	43.0	151	280	310	4
	Magnesium	11.2	15.1	39.5	64.0	68.0	4
	Sodium	0.46	0.68	1.9	2.9	3.0	4
	Potassium	0.20	0.35	0.75	1.2	1.3	4
	Sodium adsorption ratio (unitless)	0.01	0.01	0.02	0.03	0.04	4
	Alkalinity (as $CaCO_3$)	128	144	171	196	210	4
	Chloride	0.18	0.44	0.70	1.1	1.5	4
	Fluoride	0.10	--	0.80	--	1.1	3
	Silica	1.8	3.6	5.8	6.3	6.3	4

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Darby aquifer (springs)—Continued	Sulfate	2.3	5.2	359	770	830	4
	Total dissolved solids	134	171	719	1,280	1,330	4
	Nitrate plus nitrite (as N)	0.03	--	--	--	0.88	2
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
Bighorn aquifer (springs)	pH (standard units)	7.8	7.8	8.0	8.1	8.1	8
	Specific conductance (µS/cm)	245	--	--	--	281	2
	Hardness (as $CaCO_3$)	145	--	--	--	150	2
	Calcium	30.3	32.3	35.0	39.8	46.7	8
	Magnesium	6.8	11.6	14.0	17.9	22.9	8
	Sodium	0.46	0.51	0.60	1.2	1.4	7
	Potassium	0.16	0.29	0.43	1.0	1.4	8
	Sodium adsorption ratio (unitless)	0.01	0.01	0.02	0.02	0.05	8
	Alkalinity (as $CaCO_3$)	104	116	137	157	177	8
	Chloride	0.21	0.21	0.25	0.44	1.3	8
	Fluoride	0.20	--	--	--	--	1
	Silica	0.89	1.4	3.1	5.8	7.4	4
	Sulfate	1.8	6.6	11.2	25.8	41.2	8
	Total dissolved solids	104	135	160	176	188	8
	Ammonia (as N)	--	--	--	--	<0.10	3
	Nitrate plus nitrite (as N)	0.11	--	0.11	--	0.15	3
	Nitrate (as N)	0.50	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	0.02	--	0.02	3
	Arsenic	1.0	--	2.0	--	2.0	3
	Barium	<100	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	--	--	--	--	<10.0	2
	Iron	30.0	--	40.0	--	50.0	3
	Lead	50.0	--	50.0	--	50.0	3
	Manganese	10.0	--	10.0	--	10.0	3
	Mercury	<1.0	--	--	--	--	1
	Selenium	<1.0	--	--	--	--	1
	Zinc	<10.0	--	--	--	20.0	2
	Gross alpha radioactivity (picocuries per liter)	5.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	7.1	--	--	--	--	1
	Radium-226 (picocuries per liter)	2.7	--	--	--	--	1

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bighorn aquifer (springs)—Continued	Radium-228 (picocuries per liter)	1.0	--	--	--	--	1
Gallatin aquifer and confining unit (springs)	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	340	--	--	--	--	1
	Hardness (as $CaCO_3$)	200	--	--	--	--	1
	Calcium	51.0	--	--	--	--	1
	Magnesium	18.0	--	--	--	--	1
	Sodium	0.90	--	--	--	--	1
	Potassium	0.50	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.01	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	206	--	--	--	--	1
	Chloride	1.5	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	5.4	--	--	--	--	1
	Sulfate	1.3	--	--	--	--	1
	Total dissolved solids	203	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.24	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Iron, unfiltered	10.0	--	--	--	--	1
Gros Ventre aquifer and confining unit (springs)	pH (standard units)	7.9	--	--	--	8.3	2
	Specific conductance (µS/cm)	264	--	--	--	296	2
	Hardness (as $CaCO_3$)	156	--	--	--	158	2
	Calcium	36.0	--	--	--	40.0	2
	Magnesium	14.0	--	--	--	16.0	2
	Sodium	0.40	--	--	--	1.0	2
	Potassium	0.30	--	--	--	1.0	2
	Sodium adsorption ratio (unitless)	0.01	--	--	--	0.03	2
	Alkalinity (as $CaCO_3$)	143	--	--	--	162	2
	Chloride	0.40	--	--	--	1.0	2
	Fluoride	0.10	--	--	--	0.10	2
	Silica	3.5	--	--	--	--	1
	Sulfate	1.5	--	--	--	2.0	2
	Total dissolved solids	102	--	--	--	152	2
	Ammonia (as N)	--	--	--	--	<0.10	2
	Nitrate plus nitrite (as N)	0.13	--	--	--	0.17	2
	Phosphorus, unfiltered (as P)	--	--	--	--	<0.01	2
	Arsenic	<2.0	--	--	--	2.0	2
	Copper	--	--	--	--	<10.0	2

Appendix E–5. Summary statistics for water samples, Overthrust Belt, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Gros Ventre aquifer and confining unit (springs)—Continued	Iron	--	--	--	--	<30.0	2
	Lead	--	--	--	--	<50.0	2
	Manganese	--	--	--	--	<10.0	2
	Zinc	--	--	--	--	<10.0	2

Appendix E-6

Statistics for water samples, Star Valley, Wyoming

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)	pH (standard units)	7.2	7.5	7.6	7.8	8.3	81
	Specific conductance (µS/cm)	275	412	475	556	1,380	83
	Hardness (as $CaCO_3$)	117	220	235	267	334	47
	Calcium	34.0	55.0	62.0	76.0	99.0	47
	Magnesium	7.9	16.0	20.0	21.0	36.0	47
	Sodium	0.90	2.1	3.0	13.0	110	47
	Potassium	0.40	0.70	1.0	1.2	7.3	47
	Sodium adsorption ratio (unitless)	0.01	0.06	0.10	0.33	3.3	47
	Alkalinity (as $CaCO_3$)	110	168	207	240	309	47
	Chloride	0.40	1.3	2.7	10.0	197	46
	Fluoride	0.10	0.10	0.20	0.20	1.9	36
	Silica	4.9	7.9	9.2	11.0	47.0	34
	Sulfate	5.0	26.0	37.0	48.0	79.0	47
	Total dissolved solids	198	236	262	316	589	47
	Ammonia (as N)	--	0.004	0.01	0.03	1.2	40
	Nitrate plus nitrite (as N)	--	0.66	1.6	3.7	14.0	51
	Nitrate (as N)	--	0.64	1.6	3.2	14.0	38
	Nitrite (as N)	--	0.003	0.006	0.009	0.03	39
	Orthophosphate (as P)	--	0.006	0.01	0.02	0.11	38
	Phosphorus, unfiltered (as P)	--	0.009	0.02	0.04	0.04	4
	Aluminum	<100	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	--	--	--	--	<5.0	3
	Barium	<100	--	--	--	--	1
	Beryllium	<4.0	--	--	--	--	1
	Boron	--	13.1	20.3	31.4	80.0	26
	Cadmium	<0.50	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	--	--	--	--	<10.0	3
	Iron	--	0.33	1.7	8.2	610	14
	Iron, unfiltered	--	10.0	15.0	20.0	20.0	8
	Lead	--	--	--	--	<50.0	3
	Manganese	--	--	--	--	<20.0	14
	Mercury	<0.50	--	--	--	--	1
	Nickel	<20.0	--	--	--	--	1
	Selenium	--	--	--	--	<5.0	3
	Zinc	--	--	--	--	<10.0	3
	Gross alpha radioactivity (picocuries per liter)	<3.0	--	--	--	--	1

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers (wells)—Continued	Gross beta radioactivity (picocuries per liter)	2.7	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	320	430	555	690	850	6
	Uranium	1.0	--	--	--	--	1
Quaternary terrace-deposit aquifers (wells)	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	383	--	--	--	450	2
	Hardness (as $CaCO_3$)	196	--	--	--	--	1
	Calcium	49.0	--	--	--	--	1
	Magnesium	18.0	--	--	--	--	1
	Sodium	1.2	--	--	--	--	1
	Potassium	0.60	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.04	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	188	--	--	--	--	1
	Chloride	1.2	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	7.2	--	--	--	--	1
	Sulfate	17.0	--	--	--	--	1
	Total dissolved solids	206	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	0.02	2
	Nitrate plus nitrite (as N)	0.68	--	--	--	0.82	2
	Nitrate (as N)	0.66	--	--	--	0.81	2
	Nitrite (as N)	0.01	--	--	--	0.02	2
	Orthophosphate (as P)	0.01	--	--	--	0.03	2
	Boron	<10.0	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
Salt Lake aquifer (springs)	pH (standard units)	7.4	7.5	7.6	7.9	8.0	4
	Specific conductance (µS/cm)	290	338	390	444	494	4
	Hardness (as $CaCO_3$)	206	--	--	--	270	2
	Calcium	53.0	--	--	--	75.0	2
	Magnesium	18.0	--	--	--	21.0	2
	Sodium	1.0	--	--	--	2.9	2
	Potassium	0.70	--	--	--	0.80	2
	Sodium adsorption ratio (unitless)	0.03	--	--	--	0.10	2
	Alkalinity (as $CaCO_3$)	170	--	--	--	285	2

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Salt Lake aquifer (springs)—Continued	Chloride	2.1	--	--	--	2.4	2
	Fluoride	0.20	--	--	--	0.30	2
	Silica	10.0	--	--	--	12.0	2
	Sulfate	0.30	--	--	--	30.0	2
	Total dissolved solids	236	--	--	--	287	2
	Ammonia (as N)	--	--	--	--	<0.10	2
	Nitrate plus nitrite (as N)	0.20	--	1.0	--	1.6	3
	Nitrate (as N)	0.99	--	--	--	4.4	2
	Nitrite (as N)	0.01	--	--	--	--	1
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	--	1
	Arsenic	3.0	--	--	--	--	1
	Boron	30.0	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Iron	<30.0	--	--	--	--	1
	Iron, unfiltered	20.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Zinc	<10.0	--	--	--	--	1
Salt Lake aquifer (wells)	pH (standard units)	7.0	7.4	7.6	7.8	8.4	21
	Specific conductance (µS/cm)	233	447	506	547	839	21
	Hardness (as $CaCO_3$)	130	236	250	303	360	17
	Calcium	38.0	62.0	71.9	80.0	88.0	17
	Magnesium	6.6	19.0	22.0	26.0	36.0	17
	Sodium	0.80	2.0	3.2	8.1	42.0	18
	Potassium	0.70	0.80	1.0	2.0	4.3	17
	Sodium adsorption ratio (unitless)	0.03	0.07	0.10	0.20	1.6	17
	Alkalinity (as $CaCO_3$)	145	215	225	277	318	17
	Chloride	1.0	2.0	4.0	6.2	25.0	17
	Fluoride	0.05	0.10	0.10	0.20	0.49	17
	Silica	4.0	7.1	9.9	15.0	20.0	9
	Sulfate	2.8	9.0	17.0	32.0	64.0	18
	Total dissolved solids	141	252	270	315	347	17
	Ammonia (as N)	<0.10	--	--	--	0.16	11
	Nitrate plus nitrite (as N)	--	0.20	1.1	2.4	5.5	16
	Nitrate (as N)	<0.01	--	--	--	0.20	4
	Nitrite (as N)	--	--	--	--	<0.10	4
	Orthophosphate (as P)	<0.01	--	--	--	0.02	2
	Phosphorus, unfiltered (as P)	--	0.02	0.02	0.03	0.13	9
	Aluminum	<100	--	--	--	--	1

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Salt Lake aquifer (wells)—Continued	Antimony	--	--	--	--	<1.0	2
	Arsenic	--	0.81	0.99	1.2	2.0	11
	Barium	--	--	--	--	<500	3
	Beryllium	--	--	--	--	<1.0	2
	Boron	--	16.6	36.1	150	160	7
	Cadmium	--	--	--	--	<2.0	3
	Chromium	--	--	--	--	<50.0	3
	Copper	--	3.4	6.8	10.0	40.0	11
	Iron	--	7.1	41.6	220	7,030	11
	Iron, unfiltered	--	15.8	38.9	40.0	1,780	5
	Lead	--	--	--	--	<50.0	11
	Manganese	<10.0	--	--	--	140	11
	Manganese, unfiltered	<10.0	--	--	--	140	2
	Mercury	--	--	--	--	<1.0	3
	Nickel	--	--	--	--	<50.0	2
	Selenium	--	--	--	--	<5.0	3
	Zinc	--	4.2	14.7	40.0	110	10
	Gross alpha radioactivity (picocuries per liter)	--	0.85	1.5	3.5	5.0	4
	Gross beta radioactivity (picocuries per liter)	--	1.6	4.3	10.4	15	4
	Radium-226 (picocuries per liter)	--	0.40	0.75	3.0	5.0	4
	Radium-228 (picocuries per liter)	--	0.70	3.0	5.8	6.6	4
	Radon-222, unfiltered (picocuries per liter)	620	--	--	--	--	1
	Uranium	--	0.65	2.0	4.0	5.0	4
Twin Creek aquifer (springs)	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	899	--	--	--	--	1
	Hardness (as $CaCO_3$)	505	--	--	--	--	1
	Calcium	150	--	--	--	--	1
	Magnesium	32.0	--	--	--	--	1
	Sodium	5.0	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.10	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	196	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Sulfate	318	--	--	--	--	1
	Total dissolved solids	614	--	--	--	--	1

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Twin Creek aquifer (springs)—Continued	Ammonia (as N)	<0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.23	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
	Arsenic	<1.0	--	--	--	--	1
	Copper	60.0	--	--	--	--	1
	Iron	<30.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
	Zinc	30.0	--	--	--	--	1
Thaynes aquifer (wells)	pH (standard units)	7.6	--	--	--	--	1
	Specific conductance (µS/cm)	409	--	--	--	9,840	2
	Radon-222, unfiltered (picocuries per liter)	150	--	--	--	--	1
Woodside confining unit (wells)	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	444	--	--	--	--	1
Dinwoody aquifer and confining unit (hot springs)	pH (standard units)	7.5	--	--	--	--	1
	Specific conductance (µS/cm)	6,800	--	--	--	--	1
	Hardness (as $CaCO_3$)	1,300	--	--	--	--	1
	Calcium	400	--	--	--	--	1
	Magnesium	70.0	--	--	--	--	1
	Sodium	1,400	--	--	--	--	1
	Potassium	140	--	--	--	--	1
	Sodium adsorption ratio (unitless)	17.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	860	--	--	--	--	1
	Chloride	1,700	--	--	--	--	1
	Fluoride	0.60	--	--	--	--	1
	Silica	35.0	--	--	--	--	1
	Sulfate	1,100	--	--	--	--	1
	Total dissolved solids	5,250	--	--	--	--	1
	Arsenic	<50.0	--	--	--	--	1
	Barium	<500	--	--	--	--	1
	Boron	2,150	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<100	--	--	--	--	1
	Copper	<10.0	--	--	--	--	1
	Lead	500	--	--	--	--	1
	Manganese	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Nickel	<100	--	--	--	--	1

Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Dinwoody aquifer and confining unit (hot springs)—Continued	Selenium	<1.0	--	--	--	--	1
	Zinc	340	--	--	--	--	1
Madison aquifer (wells)	pH (standard units)	7.6	7.6	7.7	7.8	7.9	4
	Specific conductance (µS/cm)	489	519	563	585	592	4
	Hardness (as $CaCO_3$)	272	292	315	328	338	4
	Calcium	67.0	70.0	73.5	76.0	78.0	4
	Magnesium	22.0	26.0	32.5	36.0	37.0	4
	Sodium	1.7	4.0	5.0	7.0	7.0	5
	Potassium	0.80	0.90	1.0	1.0	1.0	4
	Sodium adsorption ratio (unitless)	0.04	0.07	0.11	0.14	0.17	4
	Alkalinity (as $CaCO_3$)	254	254	266	304	330	4
	Chloride	5.3	5.7	6.5	8.5	10.0	4
	Fluoride	0.30	0.30	0.30	0.30	0.30	5
	Silica	4.6	--	--	--	--	1
	Sulfate	10.0	31.0	33.0	33.0	37.0	5
	Total dissolved solids	244	277	311	331	349	4
	Ammonia (as N)	--	--	--	--	<0.10	3
	Nitrate plus nitrite (as N)	--	0.34	1.5	1.5	1.6	5
	Nitrate (as N)	0.34	--	--	--	--	1
	Nitrite (as N)	--	--	--	--	<0.10	3
	Orthophosphate (as P)	<0.01	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.01	--	--	--	0.02	2
	Aluminum	<100	--	--	--	--	1
	Antimony	--	--	--	--	<1.0	3
	Arsenic	--	1.1	1.3	1.5	2.0	5
	Barium	200	--	200	--	300	3
	Beryllium	--	--	--	--	<1.0	3
	Boron	<100	--	--	--	--	1
	Cadmium	--	--	--	--	<1.0	3
	Chromium	--	--	--	--	<5.00	3
	Copper	--	6.8	10.0	20.0	120	5
	Iron	<30.0	--	--	--	41.0	3
	Lead	--	--	--	--	<50.0	4
	Manganese	--	--	--	--	<10.0	3
	Mercury	--	--	--	--	<1.0	3
	Nickel	--	--	--	--	<50.0	3
	Selenium	--	--	--	--	<5.0	3
	Zinc	10.0	--	40.0	--	145	3

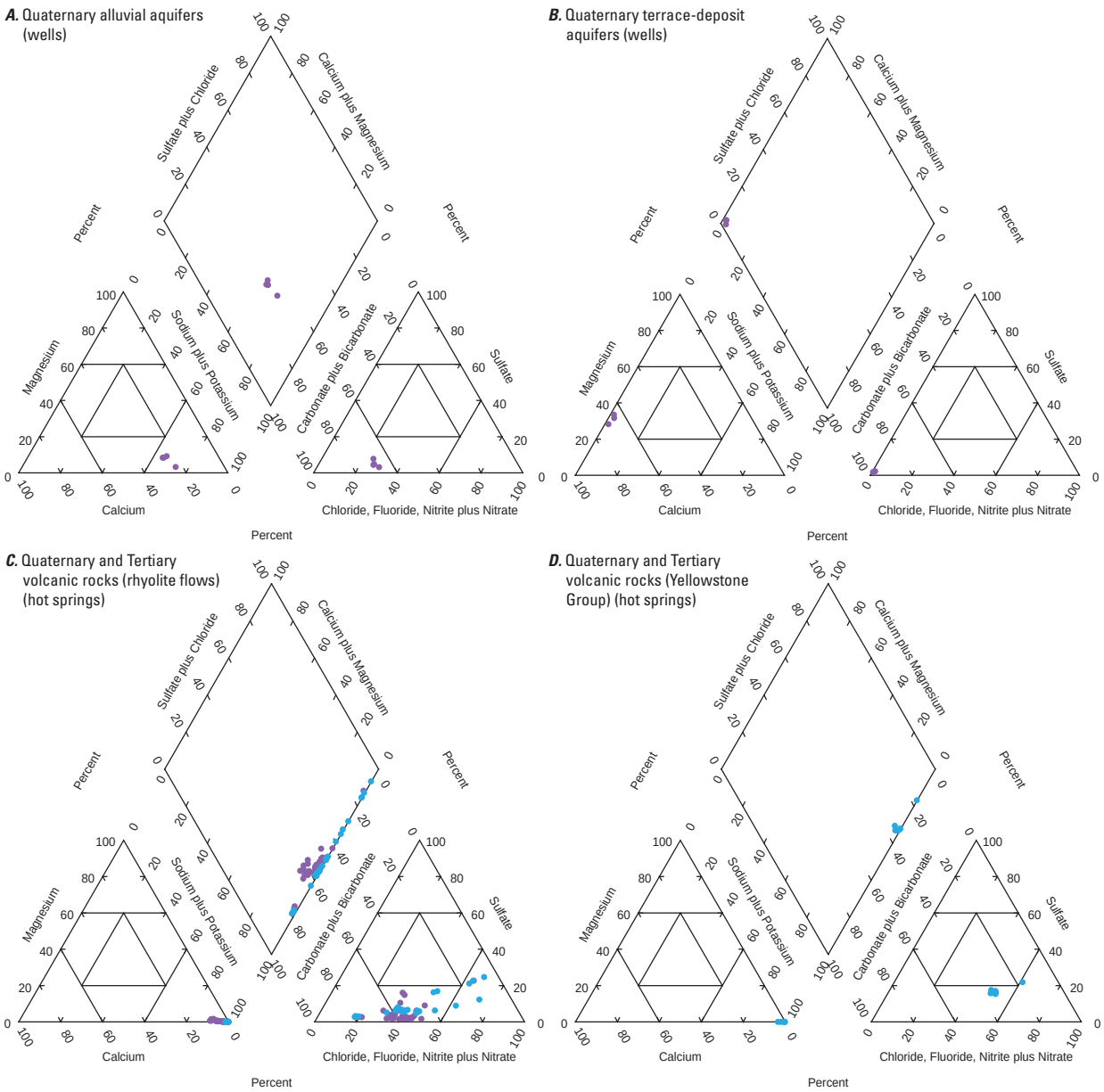
Appendix E–6. Summary statistics for water samples, Star Valley, Wyoming.—Continued

[--, not applicable; <, less than; 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	Characteristic or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer (wells)—Continued	Gross alpha radioactivity (picocuries per liter)	3.9	--	5.3	--	6.5	3
	Gross beta radioactivity (picocuries per liter)	0.20	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.30	--	--	--	0.30	2
	Radium-228 (picocuries per liter)	0.30	--	0.50	--	0.80	3
	Radon-222, unfiltered (picocuries per liter)	230	--	--	--	--	1
	Uranium	0.40	--	--	--	0.70	2
Paleozoic limestone underlying the Salt Lake Formation (wells)	pH (standard units)	8.0	--	--	--	--	1
	Specific conductance (uS/cm)	326	--	--	--	--	1
	Hardness (as $CaCO_3$)	186	--	--	--	--	1
	Calcium	37.0	--	--	--	--	1
	Magnesium	23.0	--	--	--	--	1
	Sodium	0.80	--	--	--	1.0	2
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.03	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	169	--	--	--	--	1
	Chloride	1.0	--	--	--	--	1
	Fluoride	0.10	--	--	--	0.10	2
	Sulfate	7.0	--	--	--	13.0	2
	Total dissolved solids	169	--	--	--	--	1
	Ammonia (as N)	<0.10	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.20	--	--	--	0.40	2
	Nitrite (as N)	<0.10	--	--	--	--	1
	Phosphorus, unfiltered (as P)	0.02	--	--	--	--	1
	Antimony	<1.0	--	--	--	--	1
	Arsenic	--	--	--	--	<5.0	2
	Barium	<100	--	--	--	--	1
	Beryllium	<0.50	--	--	--	--	1
	Cadmium	<0.50	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Copper	--	--	--	--	<10.0	2
	Iron	<30.0	--	--	--	--	1
	Lead	--	--	--	--	<50.0	2
	Manganese	<10.0	--	--	--	--	1
	Mercury	<0.50	--	--	--	--	1
	Nickel	<20.0	--	--	--	--	1
	Selenium	<5.0	--	--	--	--	1
	Zinc	40.0	--	--	--	--	1

Appendix F-1

Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Yellowstone Volcanic Area, Wyoming

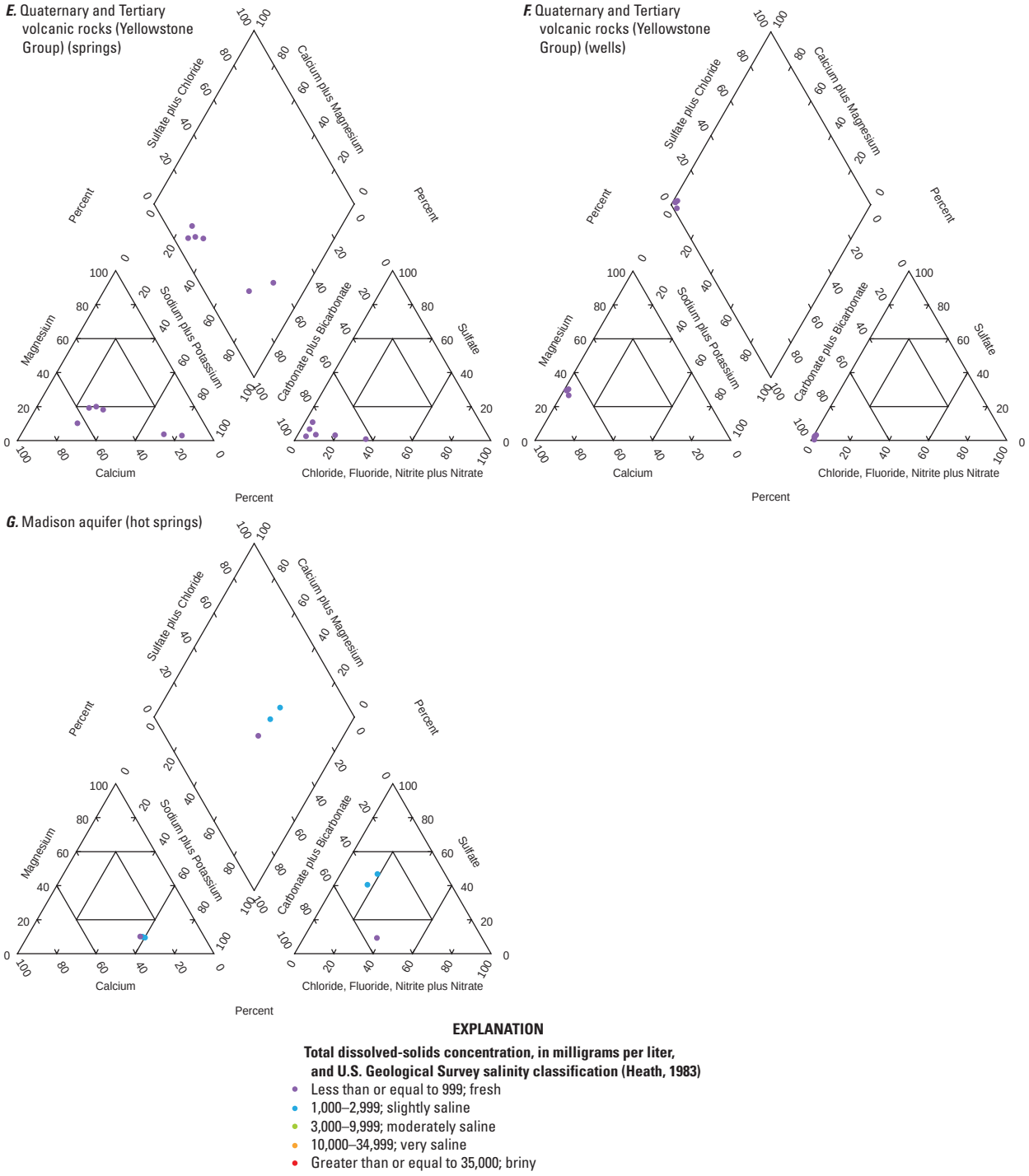


EXPLANATION

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 F–1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Yellowstone Volcanic Area, Wyoming.



EXPLANATION

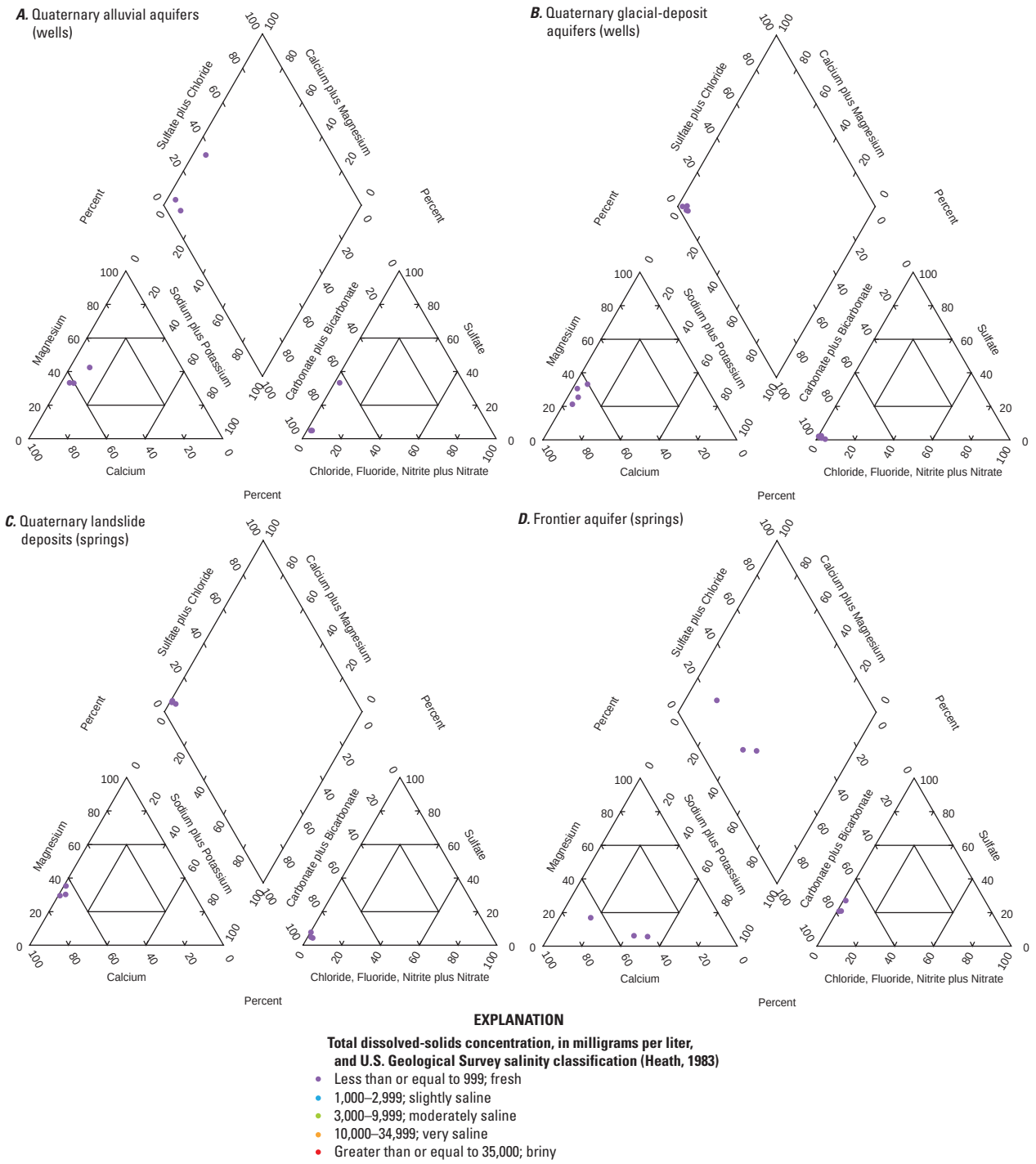
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- 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

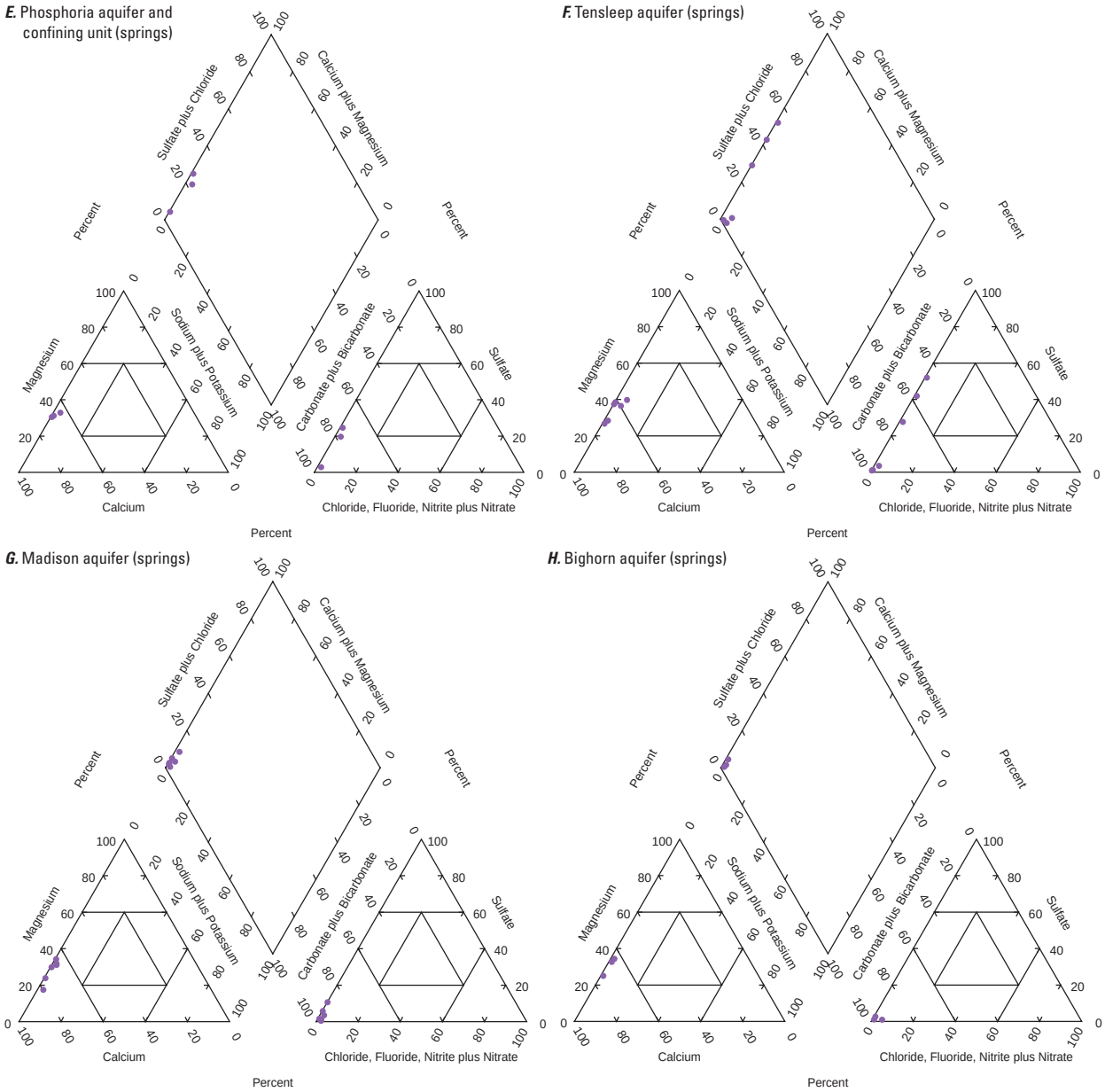
Appendix F–1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Yellowstone Volcanic Area, Wyoming.—Continued

Appendix F-2

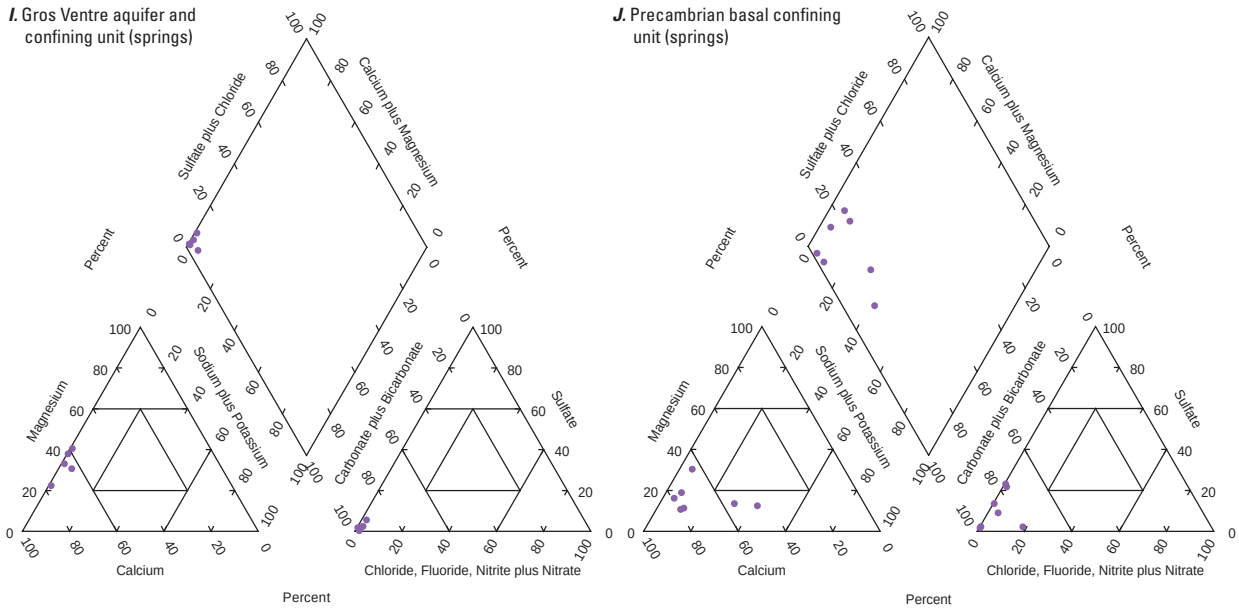
Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Northern Ranges, Wyoming



Appendix F–2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Northern Ranges, Wyoming.



Appendix F–2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Northern Ranges, Wyoming.—Continued



EXPLANATION

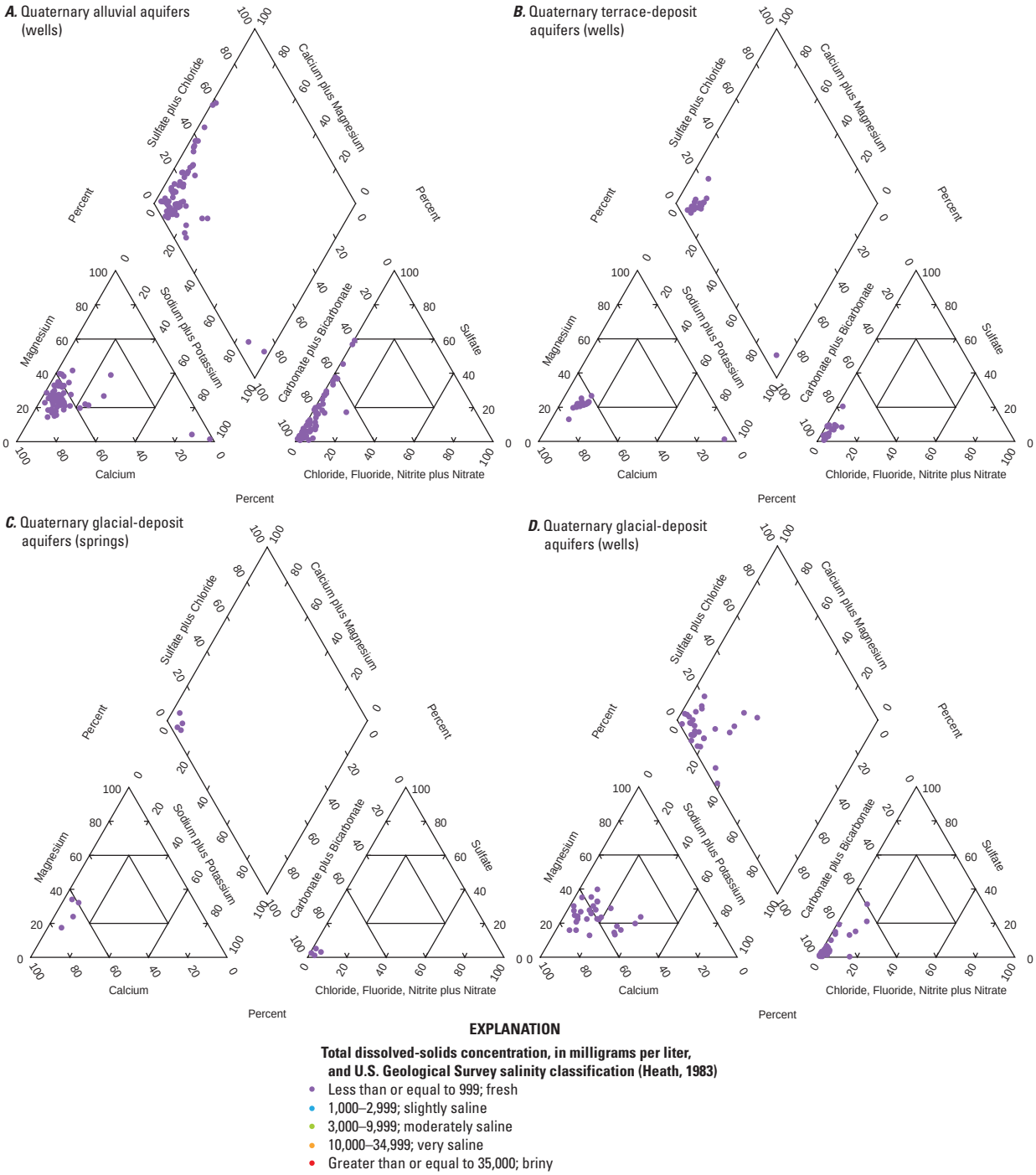
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- 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

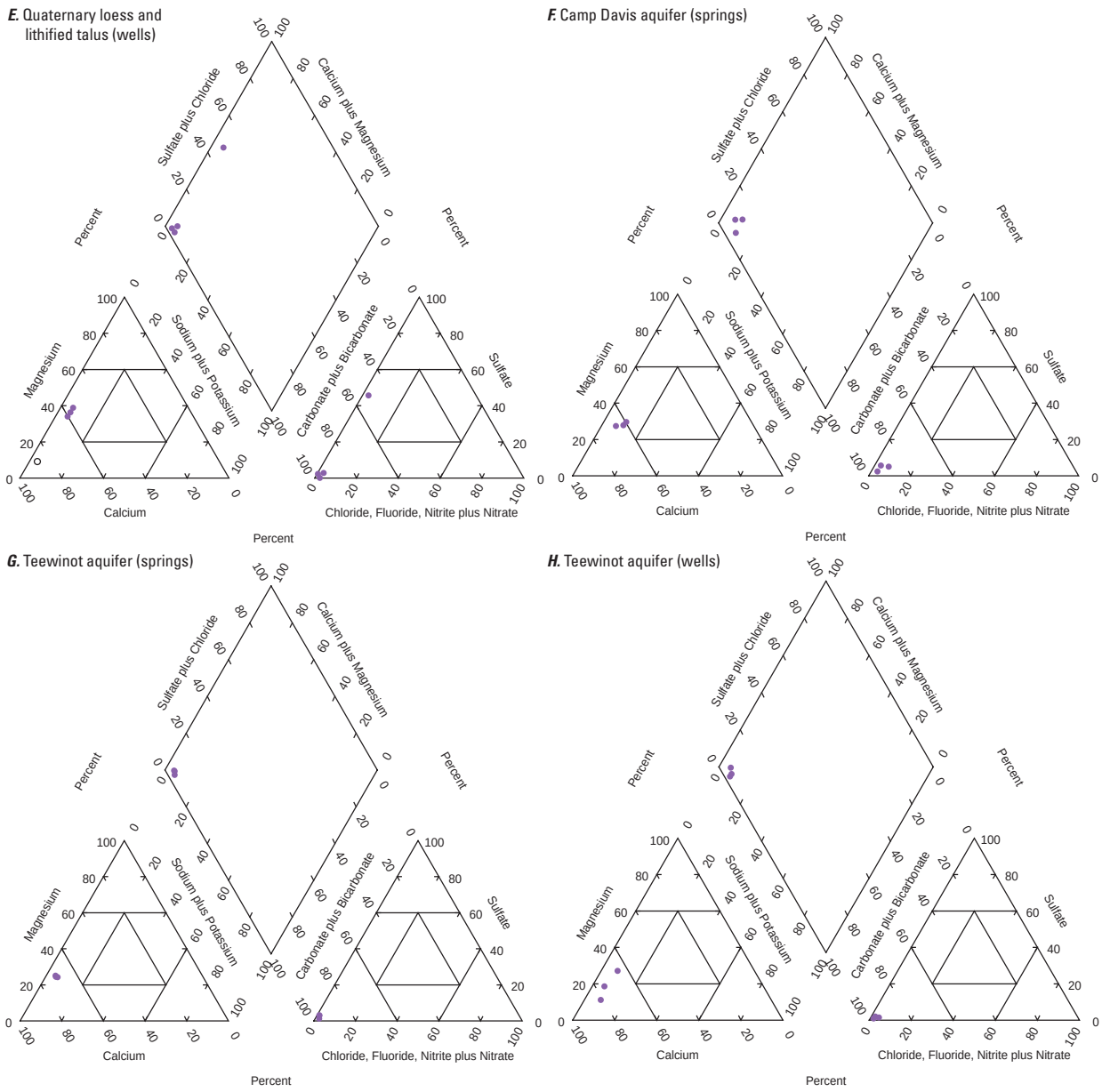
Appendix F–2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Northern Ranges, Wyoming.—Continued

Appendix F-3

Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Jackson Hole, Wyoming



Appendix F–3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs near Jackson Hole, Wyoming.



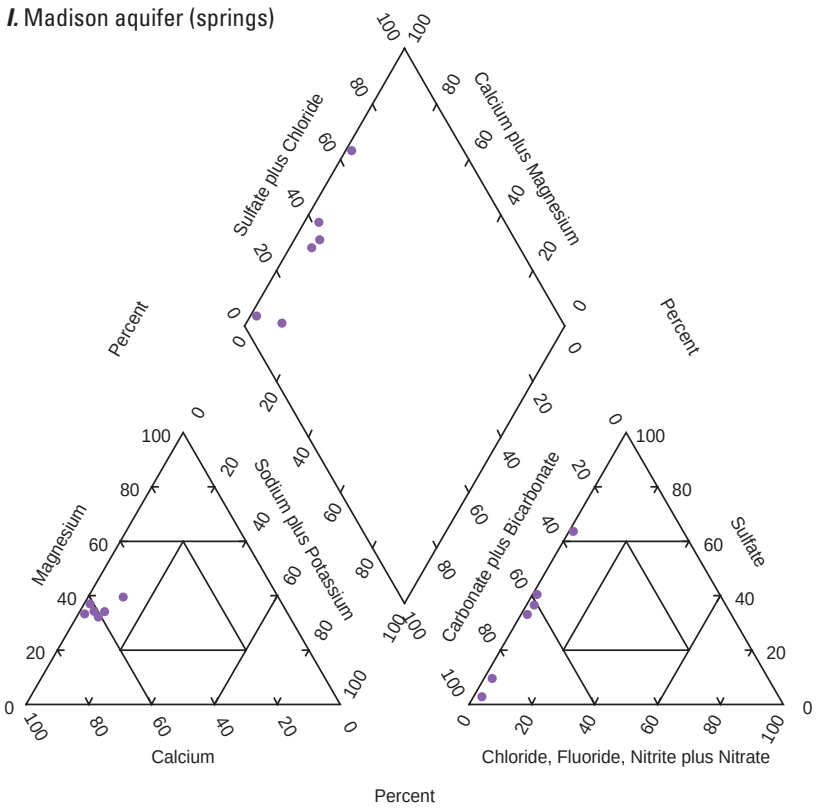
EXPLANATION

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 F–3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs near Jackson Hole, Wyoming.—Continued

I. Madison aquifer (springs)



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

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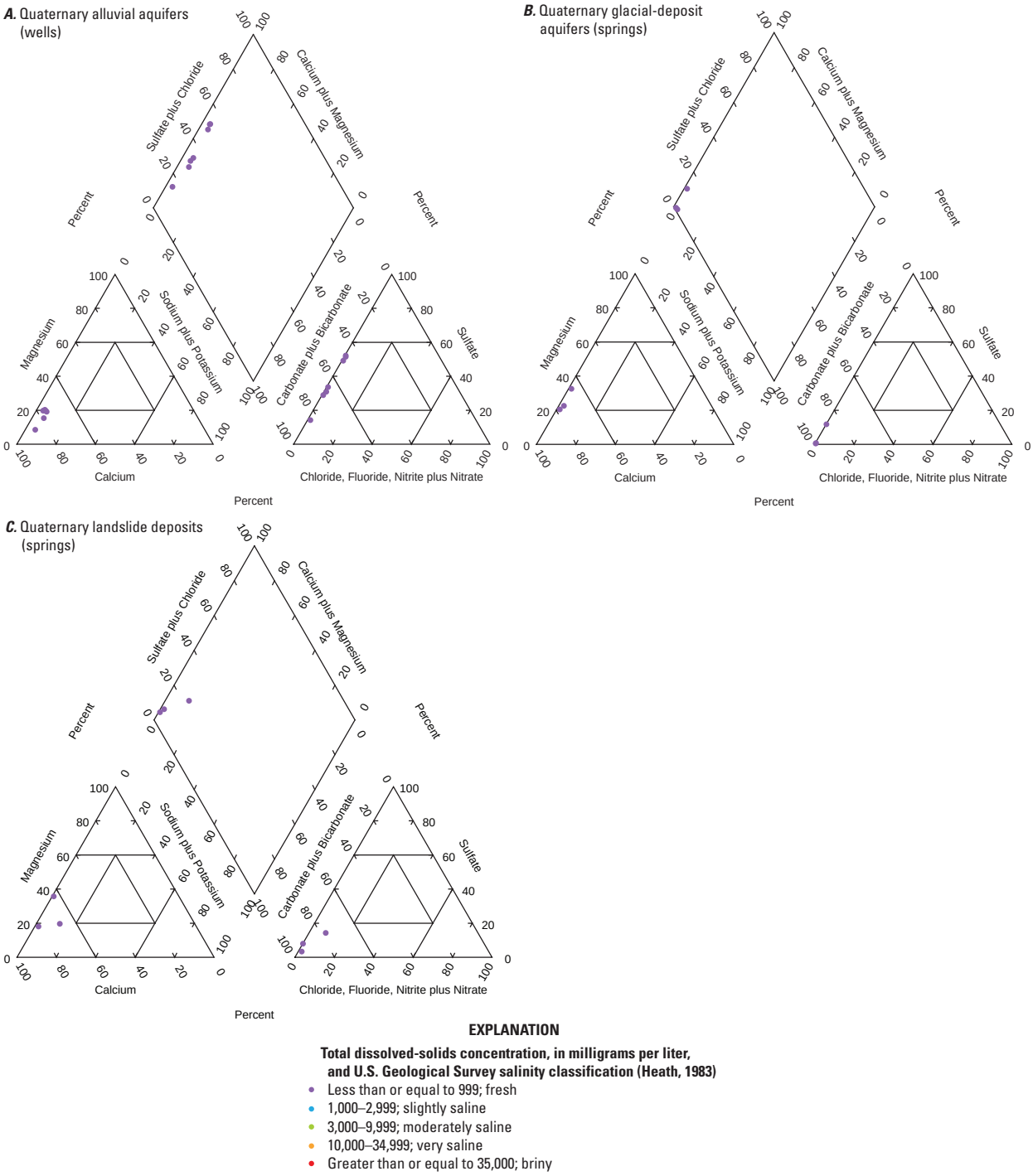
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix F–3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs near Jackson Hole, Wyoming.—Continued

Appendix F-4

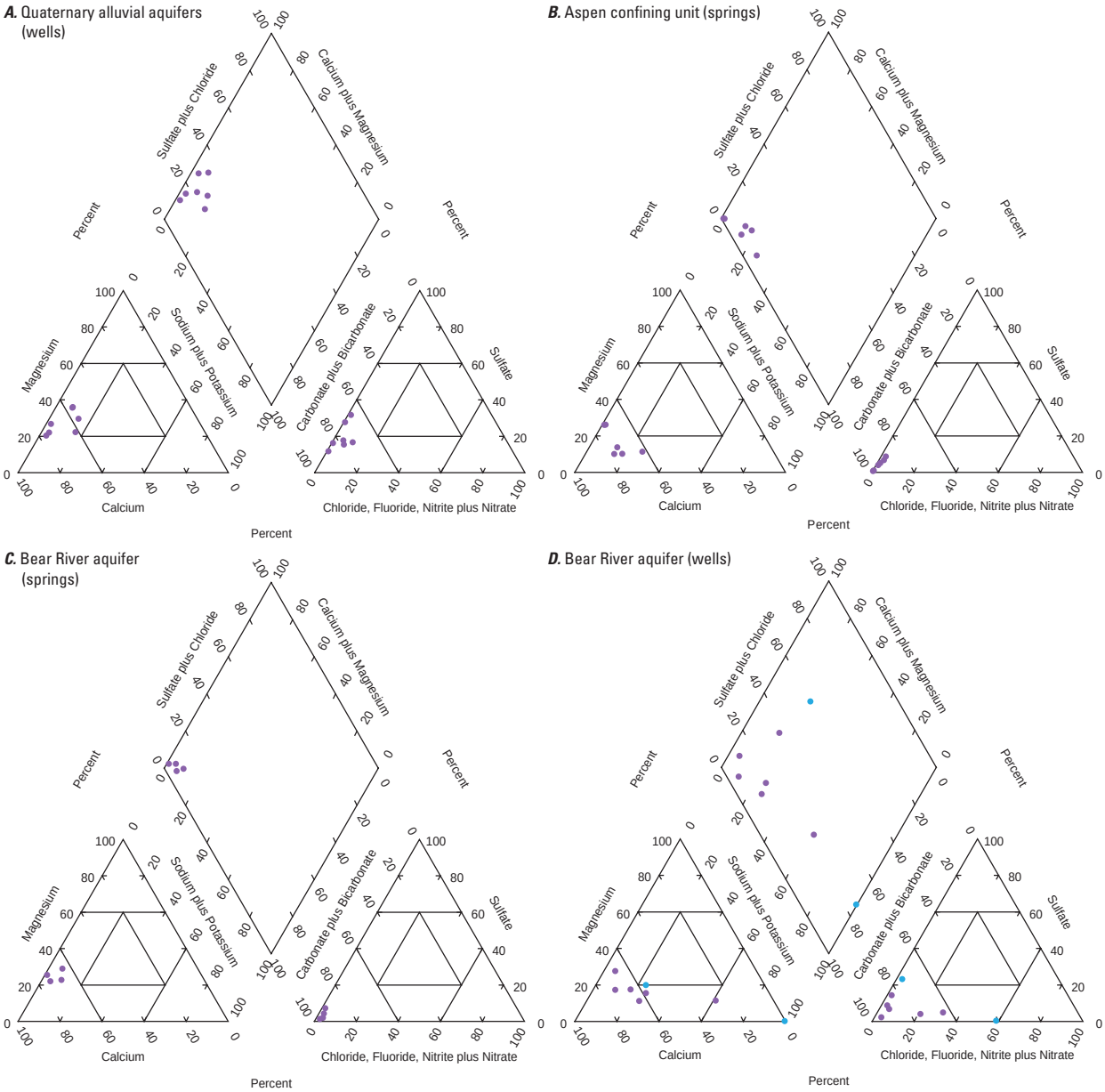
Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Green River and Hoback basins, Wyoming



Appendix F–4. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Green River and Hoback Basins, Wyoming.

Appendix F-5

Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Overthrust Belt, Wyoming

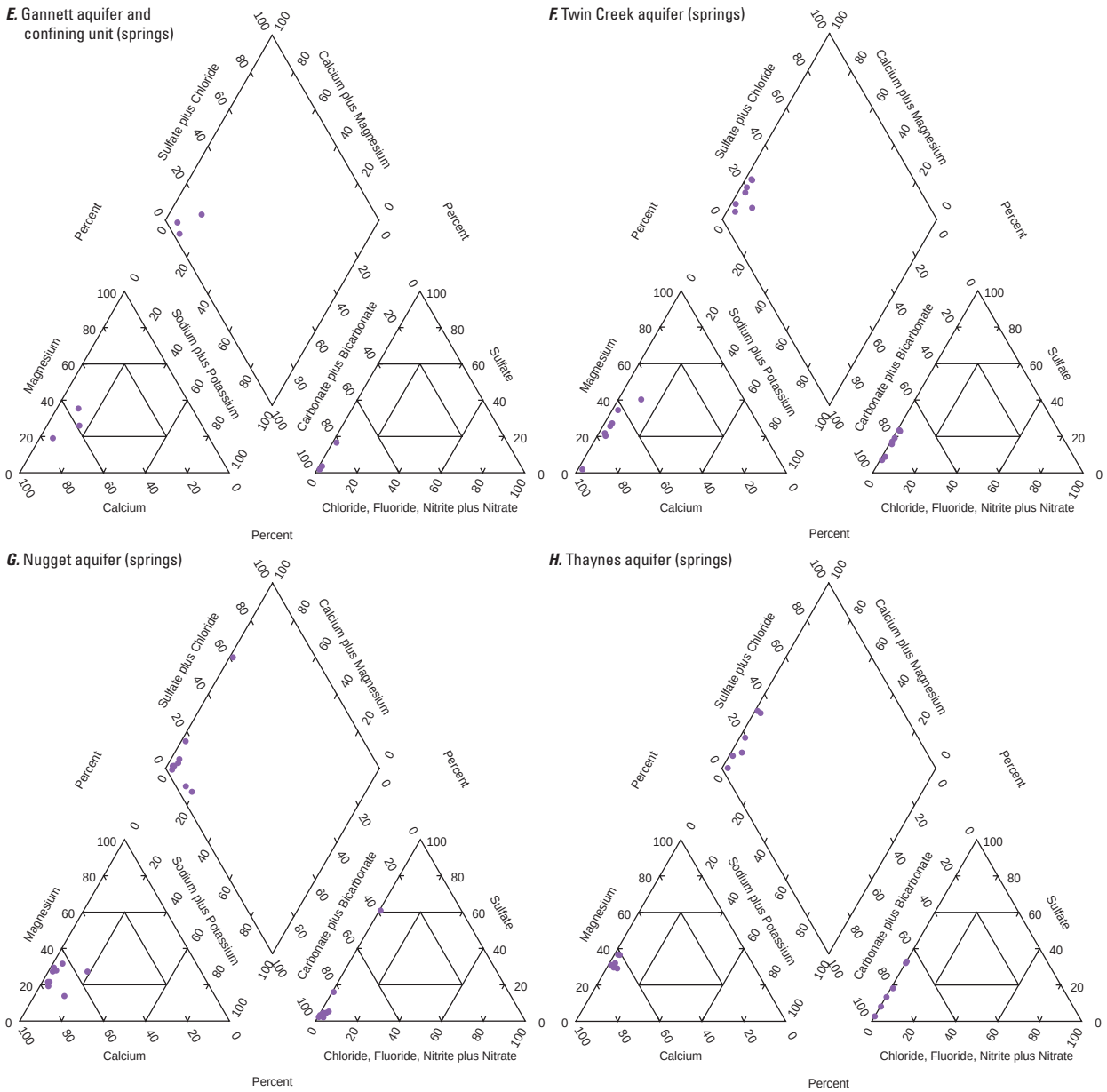


EXPLANATION

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 F–5. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Overthrust Belt, Wyoming.

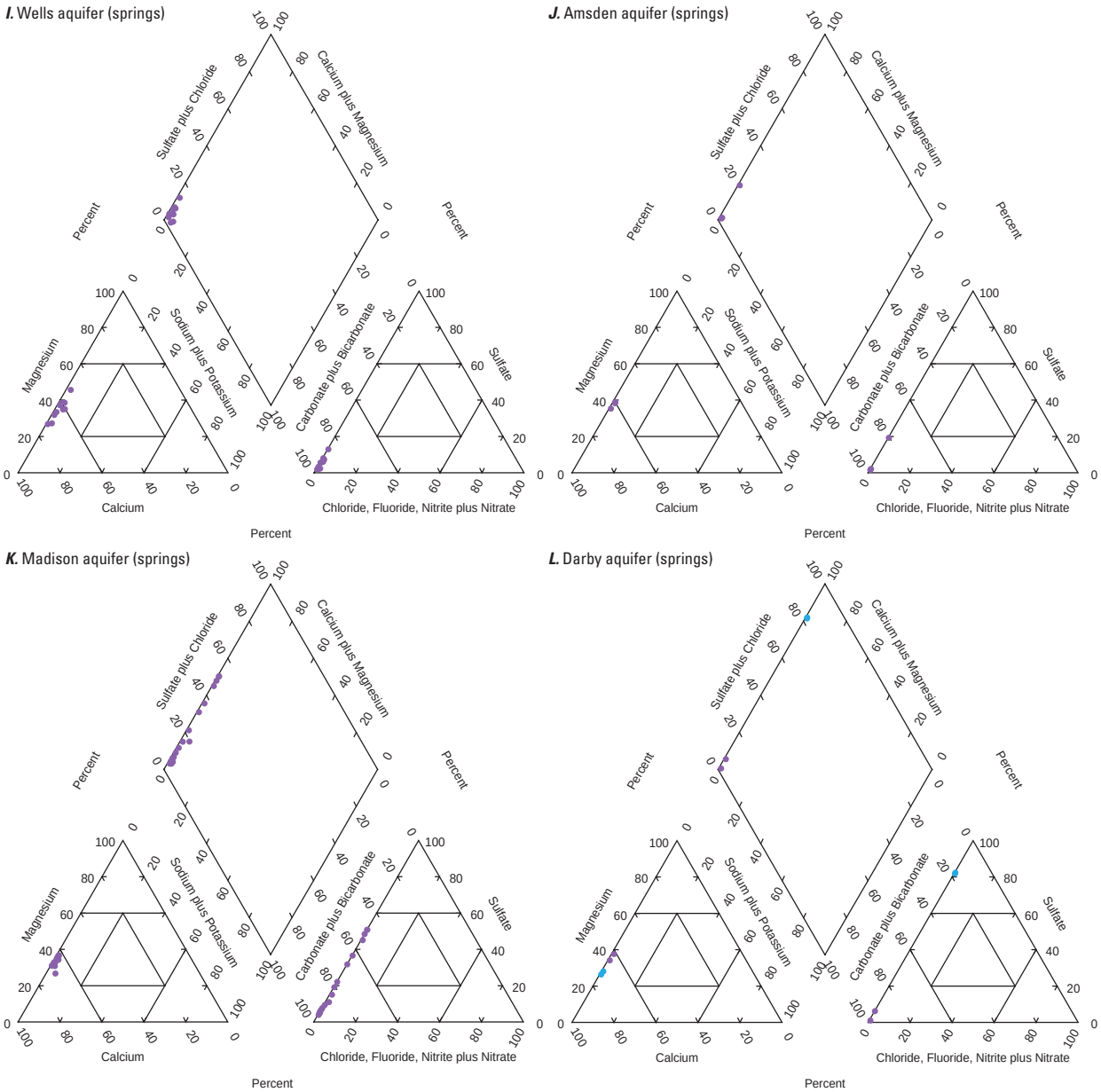


EXPLANATION

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 F–5. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Overthrust Belt, Wyoming.—Continued



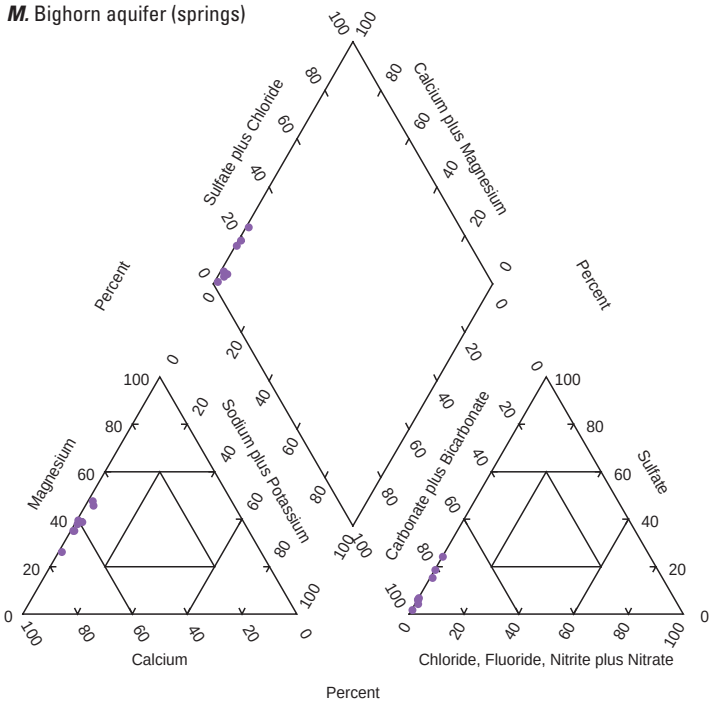
EXPLANATION

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 F–5. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Overthrust Belt, Wyoming.—Continued

M. Bighorn aquifer (springs)



EXPLANATION

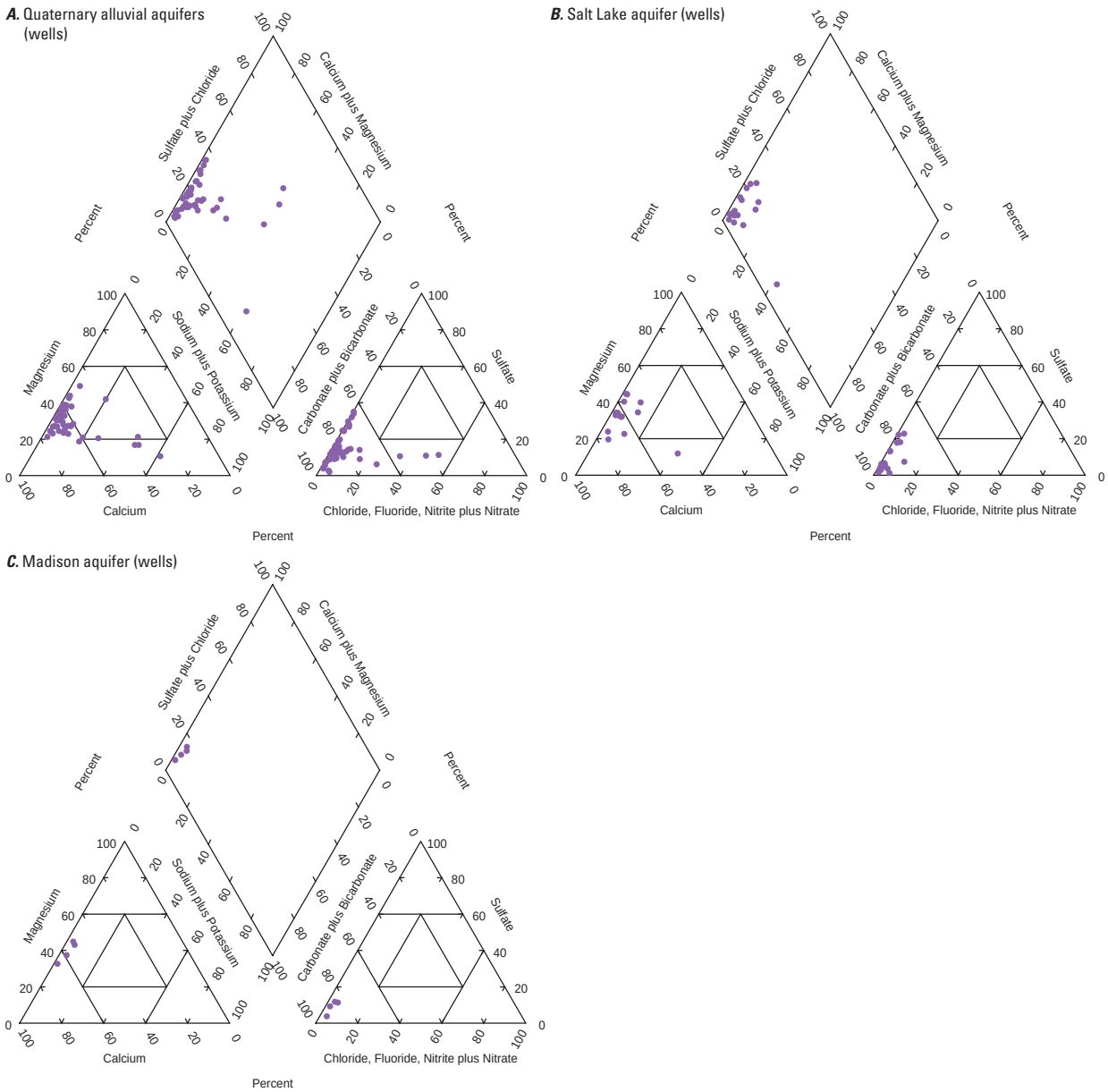
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- 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 F–5. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in the Overthrust Belt, Wyoming.—Continued

Appendix F-6

Trilinear diagrams showing major-ion composition and dissolved-solids for groundwater samples, Star Valley, Wyoming



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

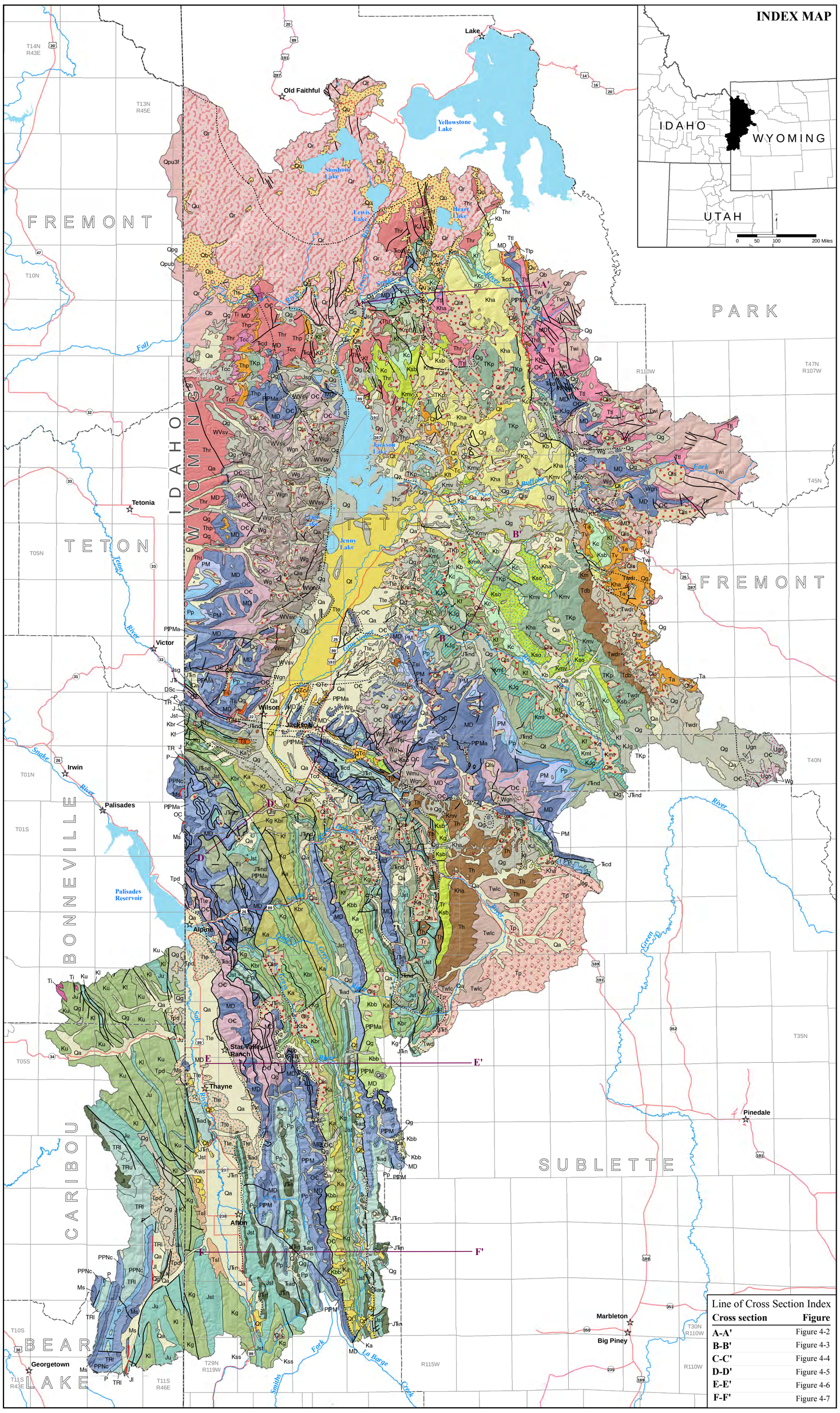
Appendix F–6. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from wells and springs in Star Valley, Wyoming.

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

Snake/Salt River Basin Plan II - Available Groundwater Determination Technical Memorandum

Plate I
Bedrock Geology - Snake/Salt River Basin



Line of Cross Section Index

Cross section	Figure
A-A'	Figure 4-2
B-B'	Figure 4-3
C-C'	Figure 4-4
D-D'	Figure 4-5
E-E'	Figure 4-6
F-F'	Figure 4-7

Bedrock Geology - Snake/Salt River Basin Wyoming and Idaho

compiled by
Seth J. Wittke, James E. Stafford, and Tomas Gracias

Magnetic Declination = 11° 49' E
at center of map
(March 7, 2013)

0 5 10 15 20 25 30 Miles

Scale 1:400,000

Explanation

- U.S. highway
- State highway
- A—A' Line of cross section
- Normal fault—dotted where concealed; ball & bar on downthrown block
- Thrust fault—dotted where concealed; sawteeth on upper (tectonically higher) plate
- City or town
- Township boundary
- County boundary
- State boundary
- Lake or reservoir
- River or creek

Bedrock Geology

Wyoming Geologic Units

CENOZOIC

Quaternary

- Qa — Alluvium & colluvium
- Qt — Gravel, pediment, and fan deposits — may include some glacial deposits and Tertiary gravels
- Qg — Glacial deposits
- Qls — Landslide deposits
- Qu — Undivided surficial deposits
- Qb — Basalt flows and intrusive igneous rocks
- Qr — Rhyolite flows, tuff, and intrusive igneous rocks

Quaternary and Tertiary

- QTc — Conglomerate (Pleistocene or Pliocene)

Tertiary

- Thr — Huckleberry Ridge Tuff of Yellowstone Group
- Ti — Intrusive and extrusive igneous rocks
- Thl — Heart Lake Conglomerate
- Tsl — Salt Lake Formation
- Tsi — Shooting Iron Formation
- Tcc — Conant Creek Tuff
- Tte — Teewinot Formation
- Tr — Red conglomerate on top of Hoback and Wyoming Ranges
- Tcd — Camp Davis Formation
- Tc — Colter Formation
- Ti — Intrusive igneous rocks

Absaroka Volcanic Supergroup

Thorofare Creek Group

- Twi — Wiggins Formation
- Ttl — Two Ocean and Langford Formations
- Ta — Aycross Formation

Thorofare Creek and Sunlight Groups

- Ttp — Trout Peak Trachyandesite
- Tts — Two Ocean, Langford, Trout Peak, and Wapati Formations
- Thp — Hominy Peak Formation
- Tv — Volcanic conglomerate
- Tcs — Conglomerate of Sublette Range
- Twd — Diamictite and sandstone in the Wasatch Formation
- Twdr — Wind River Formation
- Twlc — La Barge and Chappo Members of Wasatch Formation
- Tp — Pass Peak Formation and equivalents
- Tdb — Devils Basin Formation
- Th — Hoback Formation

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

- TKp — Hoback Formation

MESOZOIC

Cretaceous

- Kha — Harebell Formation
- Km — Meeteetse Formation
- Kmv — Mesaverde Formation
- Kso — Sohare Formation
- Ksb — Sohare Formation and Bacon Ridge Sandstone
- Kb — Bacon Ridge Sandstone
- Kc — Cody Shale
- Kbb — Blind Bull Formation
- Kf — Frontier Formation
- Kft — Frontier Formation, and Mowry and Thermopolis Shales
- Kmt — Mowry and Thermopolis Shales
- Kss — Sage Junction, Quealy, Cokeville, Thomas Fork, and Smiths Formations
- Kws — Wayan and Smiths Formations
- Ka — Aspen Shale
- Kbr — Bear River Formation
- Kg — Gannett Group

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJg — Cloverly, Morrison, Sundance, and Gypsum Spring Formations

Jurassic

- Jst — Stump Formation, Preuss Sandstone or Redbeds, and Twin Creek Limestone
- Jsg — Sundance and Gypsum Spring Formations

Jurassic and Triassic

- JTr — Sundance and Gypsum Spring Formations, and Nugget Sandstone
- JTrn — Nugget Sandstone
- JTrnd — Nugget Sandstone, and Chugwater and Dinwoody Formations

Triassic

- Trad — Ankareh Formation, Thaynes Limestone, Woodside Shale, and Dinwoody Formation
- Trcd — Chugwater and Dinwoody Formations

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian, Pennsylvanian, and Mississippian

- PPMa — Phosphoria, Wells, and Amsden Formations
- PPM — Wells and Amsden Formations
- PM — Tensleep Sandstone and Amsden Formation

Mississippian and Devonian

- MD — Madison Limestone and Darby Formation

Ordovician

- OC — Bighorn Dolomite, Gallatin Limestone, Flathead Sandstone, and Gros Ventre Formation

PRECAMBRIAN

Archean

- Wgn — Granite gneiss
- WVsv — Metasedimentary and metavolcanic rocks
- Wg — Granitic rocks
- Wmu — Metasedimentary and metavolcanic rocks
- Ugn — Oldest gneiss complex

Idaho Geologic Units

CENOZOIC

Quaternary

- Qa — Quaternary alluvium; may contain some glacial deposits and colluvium in upland
- Qg — Quaternary colluvium, fanglomerate, and talus plus some glacial debris in upland valleys
- Qpg — Pleistocene outwash, fanglomerate, flood and terrace gravels
- Qpu3f — Upper Pleistocene silicic volcanic units
- Qpub — Upper Pleistocene Snake Plain lava flows

Tertiary

- Tpd — Pliocene stream and lake deposits
- Ti — Tertiary intrusive rock

MESOZOIC

Cretaceous

- Ku — Upper Cretaceous thick detrital and fresh-water limestone beds of southeastern Idaho
- Kl — Lower Cretaceous shale, siltstone, red-bed sandstone and fresh-water limestone

Jurassic

- J — Jurassic shallow-marine to non-marine sediments in eastern Idaho
- Ju — Upper Jurassic glauconitic and variegated sandstone, siltstone, and oolitic limestone
- Jl — Lower Jurassic shaley, sandy limestone overlying red crossbedded sandstone

Triassic

- TR — Triassic shallow-marine to non-marine sediments of eastern Idaho
- TRu — Upper Triassic oxidized shale, siltstone, limestone, and conglomeratic sandstone
- TRl — Lower Triassic limestone and chert above shaley sandstone, siltstone, and limestone

PALEOZOIC

Permian

- P — Permian phosphatic sandstone, mudstone, and chert of eastern Idaho

Permian, Pennsylvanian, and Mississippian

- PPNc — Lower Permian to Middle Pennsylvanian thrusted, marine detritus of central Idaho

Mississippian

- Ms — Mississippian shallow-water coralline limestone interval of southern Idaho

Devonian and Silurian

- DSc — Devonian and Silurian thrusted, deep-water argillite and beds east-central Idaho

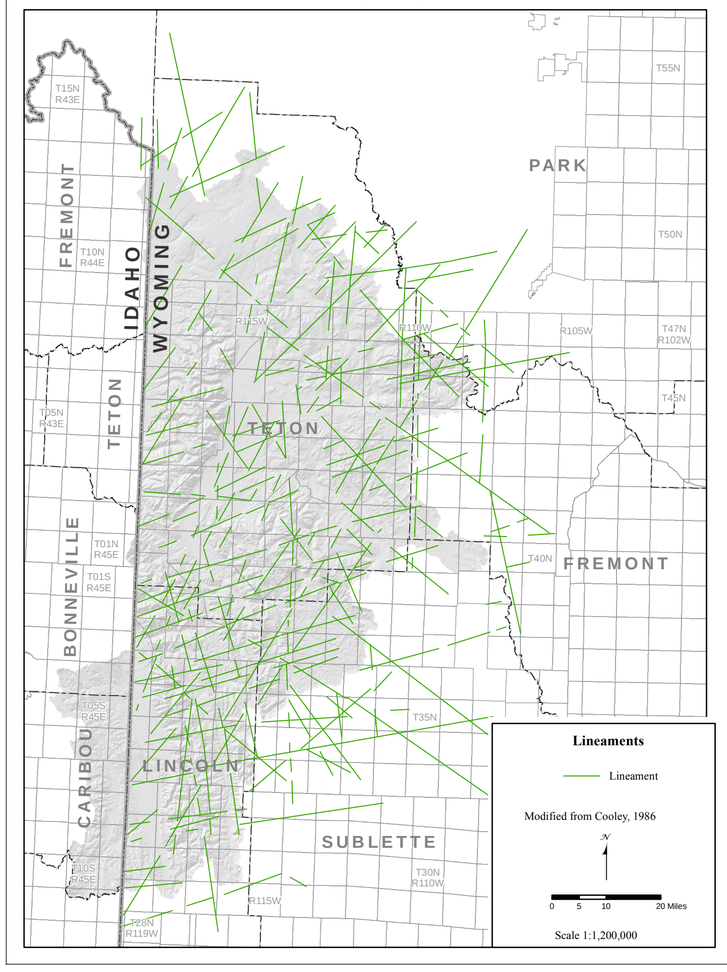
Ordovician and Cambrian

- OC — Odrovician, commonly Lower, and Cambrian marine sediments of Eastern and Southern Idaho

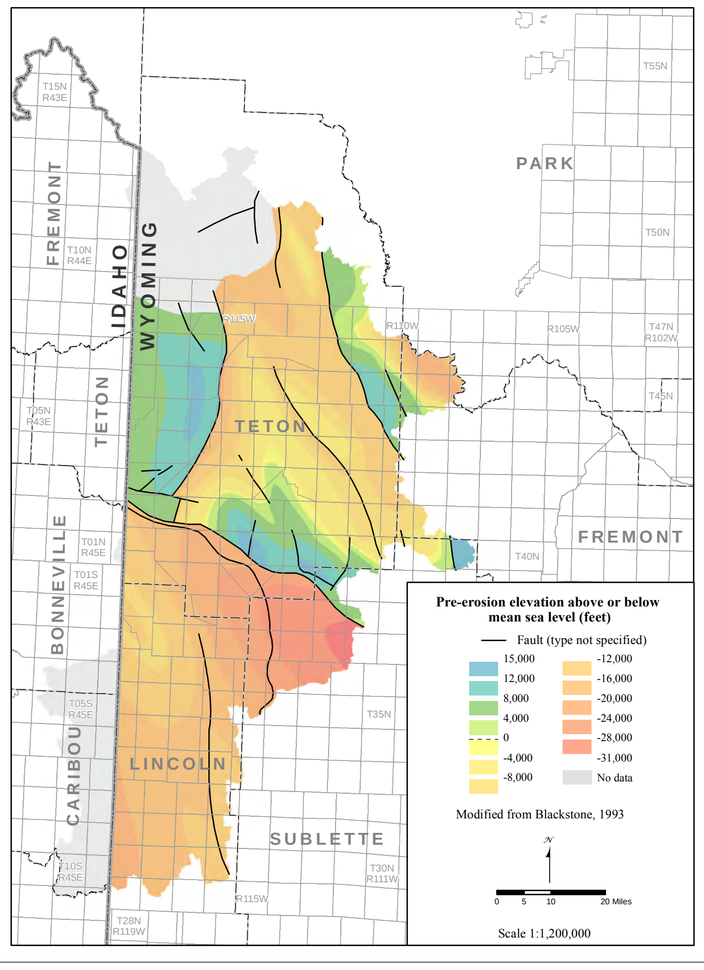
Map Projection: Universal Transverse Mercator (UTM), zone 12
False Easting: 500000, False Northing: 0
Central Meridian: -111.0 degrees West
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)

Map layout by Tomas Gracias
Map editing by Suzanne C. Luhr

Lineaments



Precambrian Basement Structure



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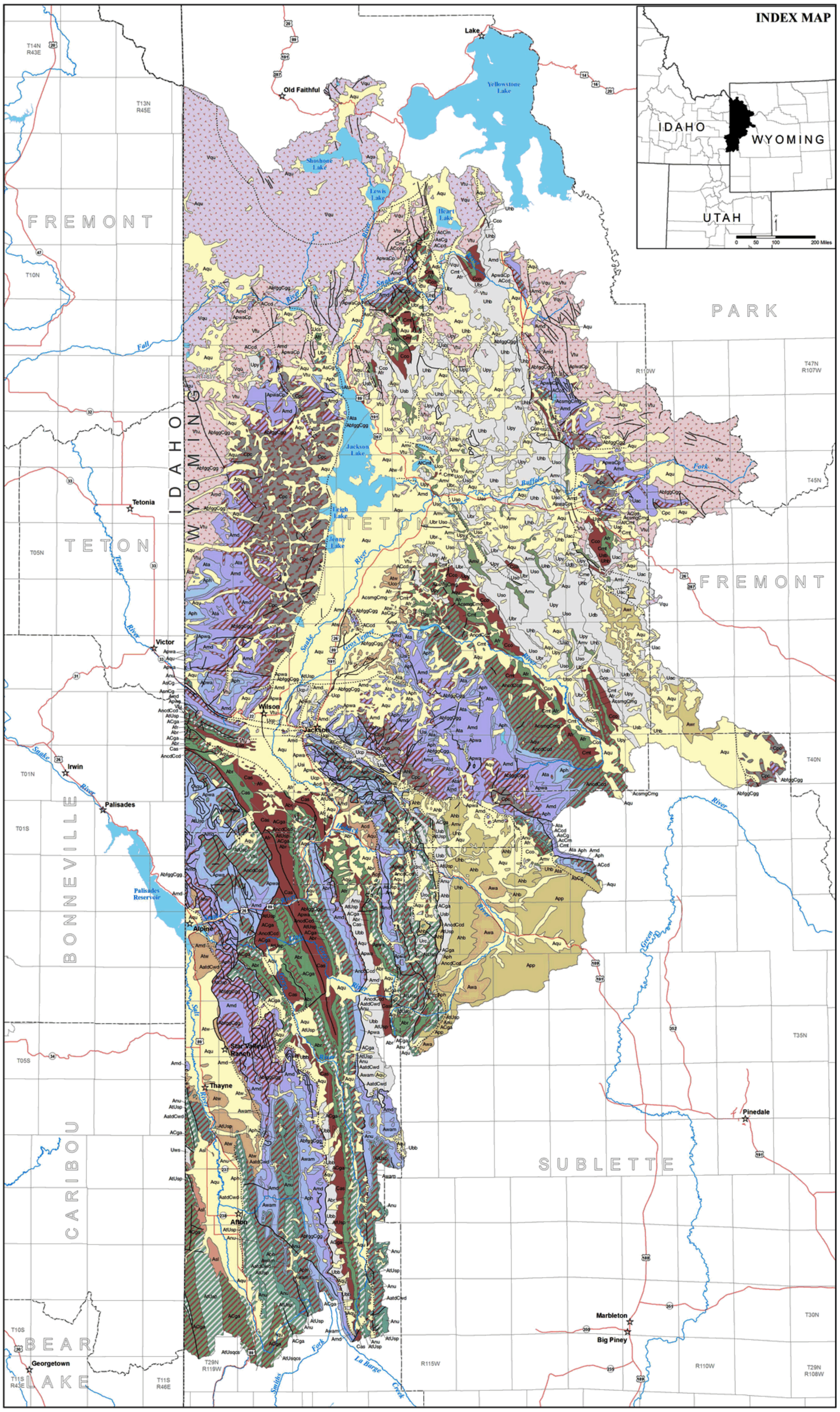
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

Snake/Salt River Basin Plan II - Available Groundwater Determination Technical Memorandum

Plate II
Hydrogeology - Snake/Salt River Basin



Map Projection: Universal Transverse Mercator (UTM), zone 12
False Easting: 500000, False Northing: 0
Central Meridian: -111.0 degrees West
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)

Map layout by Tomas Gracias
and Jim Stafford
Map editing by Suzanne C. Luhr

Hydrogeology - Snake/Salt River Basin Wyoming

compiled by
Tim Bartos and Jim Stafford

Magnetic Declination = 11° 41' 24" E
at center of map
(Feb 3, 2014)

0 5 10 15 20 25 30 Miles

Scale 1:400,000

Explanation

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

Hydrogeology

Hydrogeologic Units - Compiled from Plates 4, 5, and 6

CENOZOIC

Quaternary

- Aqu — Quaternary unconsolidated-deposit aquifer
- Vqu — Undefined Quaternary volcanic units

Quaternary and Tertiary

- Ucp — Undefined Pleistocene or Pliocene conglomerate

Tertiary

- Asl — Salt Lake aquifer
- Usi — Undefined Shooting Iron
- Acd — Camp Davis aquifer
- Atw — Teewinot aquifer
- Urc — Undefined red conglomerate
- Uco — Undefined Colter
- Uac — Undefined Aycross
- Ucs — Undefined conglomerate of the Sublette Range
- Awa — Wasatch aquifer
- Awr — Wind River aquifer
- App — Pass Peak aquifer
- Udb — Undefined Devils Basin
- Ahb — Hoback aquifer
- Vtu — Undefined Tertiary volcanic units

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

- Upy — Undefined Pinyon

MESOZOIC

Cretaceous

- Uhb — Undefined Harebell
- Cme — Meeteetse confining unit
- Amv — Mesaverde aquifer
- Uso — Undefined Sohare
- Usb — Undefined Sohare and Bacon Ridge
- Ubr — Undefined Bacon Ridge
- Coo — Cody confining unit
- Ubb — Undefined Blind Bull
- Afr — Frontier aquifer
- AfCmt — Frontier aquifer, and Mowry and Thermopolis confining units

MESOZOIC (cont.)

Cretaceous (cont.)

- Cmt — Mowry and Thermopolis confining units
- AtUsqcs — Thomas Fork aquifer, and undefined Sage Junction, Quealy, Cokeville, and Smiths
- Uws — Undefined Wayan and Smiths
- Cas — Aspen confining unit
- Abr — Bear River aquifer
- ACga — Gannett aquifer and confining unit

Cretaceous and Jurassic

- ACcm — Cloverly aquifer and Morrison confining unit
- AcmcgCrg — Cloverly and Sundance aquifers, and Morrison and Gypsum Springs confining units

Jurassic

- AtUsp — Twin Creek aquifer, and undefined Stump and Preuss
- AtCga — Sundance aquifer, and Gypsum Springs confining unit

Jurassic and Triassic

- AbfggCgg — Sundance and Nugget aquifers, and Gypsum Springs confining unit
- Anu — Nugget aquifer
- AncdCcd — Nugget aquifer, and Chugwater and Dinwoody aquifers and confining units

Triassic

- AbfggCmg — Ankareh and Thayne aquifers, Woodside confining unit, and Dinwoody aquifer and confining unit
- ACcd — Chugwater and Dinwoody aquifers and confining units

PALEOZOIC

Permian

- Aph — Phosphoria aquifer

Permian, Pennsylvanian, and Mississippian

- Apwa — Phosphoria, Wells, and Amsden aquifers
- ApwaCp — Wells and Amsden aquifers, and Phosphoria aquifer and confining unit
- Awam — Wells and Amsden aquifers

Pennsylvanian and Mississippian

- Ata — Tensleep and Amsden aquifers

Mississippian and Devonian

- Amd — Madison and Darby aquifers

Ordovician and Cambrian

- AbfggCgg — Bighorn and Flathead aquifers, and Gallatin and Gros Ventre aquifer and confining units

PRECAMBRIAN

Archean

- Cpc — Precambrian basal confining unit

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Geographic region	NWIS spring discharge, flowing: Count	Range (median) (gal/min)	NWIS hot spring discharge, flowing: Count	Range (median) (gal/min)	NWIS well yield, flowing: Count	Range (median) (gal/min)	NWIS well yield, pumped: Count	Range (median) (gal/min)	Other sources spring discharge, flowing: Count	Range (median) (gal/min)	Other sources hot spring discharge, flowing: Count	Range (median) (gal/min)	Other sources well yield, flowing: Count	Range (median) (gal/min)	Other sources well yield, pumped or unknown: Count	Range (median) (gal/min)	Other sources well yield, petroleum well data: Count	Range (median) (gal/min)	All sources spring discharge, flowing: Count	Range (median) (gal/min)	All sources well yield, pumped or flowing: Count	Range (median) (gal/min)
Cenozoic hydrogeologic units																						
Quaternary alluvial aquifers (alluvium and colluvium deposits)																						
YVA							1	25							3	25–59 (50)					4	25–59 (37.5)
NR					1	60	3	1.2–35 (20)	1	89.8					1	1,540			1	89.8	5	1.2–1,540 (35)
JH	1	2					26	1.5–3,000 (50)							64	5–2,180 (60)			1	2	90	1.5–3,000 (55)
GH							6	8–40 (18)	1	3,590					1	30			1	3,590	7	8–40 (24)
OTB							4	6–50 (8.5)							5	25–75 (50)					9	6–75 (37.5)
SV							30	4–1,200 (9)					1	12	20	5–1,500 (165)					51	4–1,500 (12)
Quaternary terrace-deposit aquifers																						
YVA							1	12							2	8; 13.6					3	8–13.6 (12)
JH	1	2					4	9–80 (33.5)							6	10–900 (26.5)			1	2	10	9–900 (17)
OTB	1	5																	1	5		
SV							1	10							1	21					2	10–21
Quaternary glacial-deposit aquifers																						
NR	1	5					1	15	1	112					3	2.5–18 (13.5)			2	5; 112	4	2.5–18 (14.2)
JH	1	20					6	60–210 (72.5)	4	1.6–2,240 (454)			2	2.8; 7.4	15	5–118 (12.5)			5	1.6–2,240 (20)	23	2.8–210 (20)
GH									2	45; 45									2	45; 45		
OTB	4	5–30 (15)																	4	5–30 (15)		
Quaternary landslide deposits																						
NR	1	50							5	224–6,730 (673)									6	50–6,730 (448)		
JH	1	50							1	359									2	50; 359		
GH									4	22–23,800 (415)									4	22–23,800 (415)		
Quaternary loess and lithified talus deposits																						
JH							2	25; 100							2	20; 20					4	20–100
Quaternary and Tertiary volcanic rocks (rhyolite flows)																						
YVA									7	1.8–449 (9)	33	0.8–300 (3.2)							40	0.8–449 (3.7)		
Quaternary and Tertiary volcanic rocks (Yellowstone Group)																						
YVA	1	5													8	5–900 (23)			1	5	8	5–900 (23)
NR	1	3																	1	3		
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks)																						
NR															1	22					1	22
JH							1	50							1	50					2	50; 50
Quaternary obsidian sand and gravel deposits underlying Lava Creek Tuff (Member B) of Yellowstone Group																						
YVA															1	10					1	10
Salt Lake aquifer																						
OTB	1	15							2	4.4; 7.5					2	255; 484			3	4.4–15 (7.5)	2	255; 484
SV	4	5–2,200 (15)			1	2	4	7–12 (9.5)	2	20; 8,000					10	50–1,000 (550)			6	5–8,000 (20)	15	2–1,000 (375)
Camp Davis aquifer																						
JH									4	1–15 (7)					1	2			4	1–15 (7)	1	2
OTB															1	10					1	10
Teewinot aquifer																						
JH	2	5; 30					1	17.4	1	144					3	10–50 (15)			3	5–144 (30)	4	10–50 (16.2)
Colter Formation																						
JH	1	1																	1	1		
Wasatch zone of the Wasatch-Fort Union aquifer (Pass Peak Formation)																						
GH	1	5					2	2; 5	2	0.4; 0.9									3	0.4–5 (0.9)	2	2; 5
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation)																						
GH	1	10					1	20	1	0.9									2	0.9; 10	1	20
Mesozoic hydrogeologic units																						
Harebell Formation																						
JH					1	12	1	20													2	12; 20
Blind Bull Formation																						
OTB	1	25							1	20									2	20; 25		
Bacon Ridge Sandstone																						
JH	1	800			1	1			1	1,120									2	800; 1,120	1	1
Frontier aquifer																						
NR									2	0.9; 112									2	0.9; 112		
JH	1	3																	1	3		
Aspen confining unit																						
JH															2	28; 100					2	28; 100
OTB	9	2–25 (8)					1	17	2	224; 224									11	2–224 (10)	1	17
Wayan Formation																						
OTB									1	10									1	10		
Bear River aquifer																						
GH																						
OTB	5	3–15 (5)					1	30	1	4					10	1–250 (35)			6	3–15 (5)	11	1–250 (30)
Gannett aquifer and confining unit																						
OTB	4	1.5–100 (30)							1	25					1	20			5	1.5–100 (25)	1	20
Stump Formation																						
JH									1	1.5									1	1.5		
OTB	1	10							1	30									2	10; 30		
Twin Creek aquifer																						
NR									1	30									1	30		
OTB	1	12							9	12.9–395 (60)									10	12–395 (56)		
SV									1	120									1	120		
Gypsum Spring confining unit																						
NR									1	45									1	45		
Nugget aquifer																						
OTB	7	8–1,400 (140)					1	8	4	70–673 (101)									11	8–1,400 (112)	1	8
Chugwater aquifer and confining unit																						
NR							1	20							1	12					2	12; 20
Ankareh aquifer																						
NR	1	10																	1	10		
OTB									2	10.9; 15									2	10.9; 15		
Thaynes aquifer																						
JH																						
OTB	12	22–1,800 (126)																	12	22–1,800 (126)		
SV			1	38															1	38		
Dinwoody aquifer and confining unit																						
NR	1	3																	1	3		
OTB									1	150									1	150		
Paleozoic and Precambrian hydrogeologic units																						
Phosphoria aquifer and confining unit																						
NR									5	45–7,630									5	45–7,630		
Tensleep aquifer																						
NR	3	2–20 (10)							15	22–8,080 (224)									18	2–8,080 (224)		
JH															3	21–250 (40)					3	21–250 (40)
GH									1	112									1	112		
Wells aquifer																						
OTB	4	7–1,500 (188)													1	75			14	5–1,500 (112)	1	75
Amsden aquifer																						
NR									1	45									1	45		
JH							1	40							1	250					2	40; 250
OTB									3	45–449 (112)									3	45–449 (112)		
Paleozoic limestone underlying the Salt Lake Formation																						
SV													1	690	1	325					2	325; 690
Madison aquifer																						
YVA	1	30							1	52	3	45–4,170 (1,390)			2	30; 60			5	30–4,170 (52)	2	30; 60
NR	1	800							22	14–4,490 (449)									23	14–4,490 (449)		
JH									8	250–7,180 (1,710)					3	6–27 (20)			8	250–7,180 (1,710)	3	6–27 (20)
GH									2	1,350; 1,800									2	1,350; 1,800		
OTB	2	10; 50							18	22–40,000 (106)	1	350			1	100			21	10–40,000 (100)	1	100
SV							1	14							9	3.7–550 (67.5)					10	3.7–550 (58.8)
Darby aquifer																						
OTB	1	10							6	30–1,100 (235)									7	10–1,100 (140)		
Bighorn aquifer																						
NR	1	500							2	112; 224									3	112–500 (224)		
OTB									13	1.4–9,960 (224)									13	1.4–9,960 (224)		
Gallatin aquifer and confining unit																						
NR									7	45–3,590 (224)									7	45–3,590 (224)		
JH															1	720					1	720
OTB	2	200; 250																	2	200; 250		
Gros Ventre aquifer and confining unit																						
NR	1	35							8	112–1,800 (224)									9	35–1,800 (224)		
JH	2	50; 75																	2	50; 75		
OTB	1	15							3	150–2,310 (824)									4	15–2,310 (487)		
Flathead aquifer																						
NR									1	22	4	0.9–449 (82.5)							5	0.9–449 (45)		
Precambrian basal confining unit																						
NR	3	2–12 (5)							12	1.8–1,350 (38.5)	2	0.2; 200							17	0.2–1,350 (20)		

Geographic region	Specific capacity, constant-rate discharge test: Count	Range [(gal/min)/ft]	Specific capacity, step tests: Count	Range [(gal/min)/ft]	Specific capacity, observation well: Count	Range [(gal/min)/ft]	Specific capacity, unspecified tests: Count	Range [(gal/min)/ft]	Specific capacity, all tests: Count	Range [(gal/min)/ft]	Transmissivity, drill stem tests: Count	Range (ft^2/day)	Transmissivity, constant-rate discharge test: Count	Range (ft^2/day)	Transmissivity, step test: Count	Range (ft^2/day)	Transmissivity, recovery test: Count	Range (ft^2/day)	Transmissivity, observation well: Count	Range (ft^2/day)	Transmissivity, unspecified tests: Count	Range (ft^2/day)	Transmissivity, all tests: Count	Range (ft^2/day)	Porosity: Count	Range (percent)	Hydraulic conductivity, constant-rate discharge test: Count	Range (ft/day)	Hydraulic conductivity, recovery test: Count	Range (ft/day)	Hydraulic conductivity, observation well: Count	Range (ft/day)	Hydraulic conductivity, all tests: Count	Range (ft/day)	Storativity/storage coefficient: Count	Range (unitless)	Sources of data (listed on bottom of plate)
Cenozoic hydrogeologic units																																					
Quaternary alluvial aquifers (alluvium and colluvium deposits)																																					
YVA	1	16							1	16																											1; 10
NR							3	0.03–70	3	0.03–70																											1; 9; 10; 40; 46
JH	9	2.7–100					51	0.08–530	60	0.08–530			3	1,470–2,080							13	188–6,700	16	188–6,700											1	0.04	1; 2; 8; 10; 27; 28; 30; 34; 36; 38; 39; 40; 46
GH							1	7.5	1	7.5											1	800	1	800													1; 2; 9; 46
OTB							4	0.5–38	4	0.5–38											1	2,680	1	2,680													1; 2; 12; 39; 46
SV	2	170; 260	2	48; 480			12	1.3–250	16	1.3–480			2	33,500; 42,200	1	49,600					4	121–49,600	7	121–49,600			1	620					1	620	1	0.0003	1; 2; 12; 14; 18; 45; 46; 47; 48; 54; 56
Quaternary terrace-deposit aquifers																																					
YVA							1	7.5	1	7.5																											1; 40; 42; 43
JH							5	3.7–190	5	3.7–190																											1; 8; 10; 28; 40; 46
OTB																																					1; 12; 46
SV																																					1; 12; 45; 46
Quaternary glacial-deposit aquifers																																					
NR							2	0.1; 2.3	2	0.1; 2.3											1	241	1	241													1; 2; 10; 35; 40; 46
JH	3	1–11					13	0.2–19	16	0.2–19			2	188; 509			1	161	1	188	2	20.1; 26.8	6	20.1–509													1; 2; 8; 9; 10; 26; 29; 34; 36; 40; 46
GH																																					35
OTB																																					1; 2; 12; 46
Quaternary landslide deposits																																					
NR																																					1; 35; 40; 46
JH																																					1; 9; 40; 46
GH																																					35
Quaternary loess and lithified talus deposits																																					
JH							4	0.25–9.1	4	0.25–9.1											2	80; 400	2	80; 400													1; 2; 40; 46
Quaternary and Tertiary volcanic rocks (rhyolite flows)																																					
YVA																																					7; 9; 49
Quaternary and Tertiary volcanic rocks (Yellowstone Group)																																					
YVA	1	2.3					7	0.05–11	8	0.05–11			1	670			2	13.4; 121			1	6.7	4	6.7–670													1; 40; 42; 43
NR																																					1; 40
Quaternary and Tertiary volcanic rocks (Tertiary intrusive rocks)																																					
NR							1	0.8	1	0.8											1	67	1	67													2; 10
JH							1	17	1	17																											1; 2; 40; 46
Quaternary obsidian sand and gravel deposits underlying Lava Creek Tuff (Member B) of Yellowstone Group																																					
YVA	1	0.26							1	0.26			1	32.2									1	32.2													10; 33
Salt Lake aquifer																																					
OTB	2	29; 58							2	29; 58			1	180,000									1	180,000			1	1,800					1	1,800			1; 2; 12; 15; 46; 48; 50
SV	6	2.3–44	1	3.9			5	0.67–170	12	0.67–170			5	1,000–75,700	4	161–25,800			2	24,100; 24,300			11	161–75,700	1	22	4	5.9–270	2	1.3; 110	2	100; 110	8	1.3–270	2	0.02; 0.03	1; 2; 12; 18; 19; 20; 21; 45; 46; 48; 51; 52; 53; 55
Camp Davis aquifer																																					
JH																																					2; 5; 30
OTB																																					2
Teewinot aquifer																																					
JH							2	1; 1.5	2	1; 1.5											3	134–9,380	3	134–9,380													1; 2; 8; 9; 10; 40; 46
Colter Formation																																					
JH																																					1; 40; 46
Wasatch zone of the Wasatch-Fort Union aquifer (Pass Peak Formation)																																					
GH							1	0.25	1	0.25																											1; 9; 46
Fort Union zone of the Wasatch-Fort Union aquifer (Hoback Formation)																																					
GH							1	2.9	1	2.9																											1; 2; 9; 10; 11
Mesozoic hydrogeologic units																																					
Harebell Formation																																					
JH							1	2	1	2																											1; 40; 46
Blind Bull Formation																																					
OTB																																					1; 2; 12; 46
Bacon Ridge Sandstone																																					
JH																																					1; 9; 40; 46
Frontier aquifer																																					
NR																																					9
JH																																					1; 40; 46
Aspen confining unit																																					
JH							2	2.1; 2.8	2	2.1; 2.8																											39
OTB							1	8.5	1	8.5											1	804	1	804													1; 2; 6; 12; 46
Wayan Formation																																					
OTB																																					2
Bear River aquifer																																					
GH											1	0.09											1	0.09													2
OTB							7	0.2–7.8	7	0.2–7.8											3	40.2–1,270	3	40.2–1,270													1; 2; 12; 39; 40; 46
Gannett aquifer and confining unit																																					
OTB																																					1; 2; 12; 46
Stump Formation																																					
JH																																					5
OTB																																					1; 2; 12; 46
Twin Creek aquifer																																					
NR																																					2
OTB											1	0.16											1	0.16													1; 2; 12; 15; 16; 17; 46; 48
SV																																					48
Gypsum Spring confining unit																																					
NR																																					35
Nugget aquifer																																					
OTB																																					1; 2; 6; 12; 46; 48
Chugwater aquifer and confining unit																																					
NR																																					1; 2; 10; 40; 46
Ankareh aquifer																																					
NR																																					1; 40
OTB																																					15
Thaynes aquifer																																					
JH											1	1.11											1	1.11													2
OTB																																					2; 6; 48
SV																																					1; 2; 4; 12; 46
Dinwoody aquifer and confining unit																																					
NR																																					1; 40
OTB																																					2
Paleozoic and Precambrian hydrogeologic units																																					
Phosphoria aquifer and confining unit																																					
NR											1	4.56											1	4.56													2; 35
Tensleep aquifer																																					
NR																																					1; 9; 11; 35; 40; 46
JH							2	1.5–1.9	2	1.5–1.9	3	0.43–5.09									2	402–469	5	0.43–469													2
GH																																					35
Wells aquifer																																					
OTB							1	0.96	1	0.96																											1; 2; 6; 12; 39; 46
Amsden aquifer																																					
NR																																					35
JH							1	1.9	1	1.9																											1; 10; 40; 46
OTB																																					6
Paleozoic limestone underlying the Salt Lake Formation																																					
SV	1	49							1	49			1	13,100									1	13,100													23; 48; 55
Madison aquifer																																					
YVA	1	0.3					1	1.5	2	0.3; 1.5			1	80.4							1	268	2	80.4; 268													1; 2; 10; 31; 32; 40
NR											1	0.25											1	0.25													1; 2; 3; 35; 40
JH	1	0.2					2	5; 46	3	0.2–46											2	536; 6,700	2	536; 6,700													2; 7; 8; 9; 10; 11
GH																																					35
OTB																																					1; 2; 4; 6; 12; 22; 46
SV	2	3.9; 6.7			1	4.2	5	0.07–29	8	0.07–29			2	442; 4,420			1	3,480	1	1,180	1	1,180	5	442–4,420											3	0.005–0.008	1; 41; 44; 45; 48; 57
Darby aquifer																																					
OTB																																					1; 2, 6; 12; 13; 19; 46
Bighorn aquifer																																					
NR																																					1; 35; 40
OTB																																					6; 13; 19; 24; 25
Gallatin aquifer and confining unit																																					
NR																																					7; 9; 35
JH							1	140	1	140											1	13,400	1	13,400													2; 10
OTB																																					1; 2; 12; 46
Gros Ventre aquifer and confining unit																																					
NR																																					1; 9; 11; 35; 40
JH																																					1
OTB																																					1; 12; 23; 46; 48; 55
Flathead aquifer																																					
NR																																					7; 9; 11; 35
Precambrian basal confining unit																																					
NR																																					1; 3; 7; 9; 10; 28; 35; 37; 40; 46

[gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; ft^2/day, feet squared per day; ft/day, feet per day. Geographic regions: YVA, Yellowstone Volcanic Area; NR, Northern Ranges; JH, Jackson Hole; GH, Green River and Hoback Basins; OTB, Overthrust Belt; SV, Star Valley]

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Plate 3. Summaries of spring discharge, well yield, and hydraulic properties, Snake/Salt River Basin, Wyoming.

ERATHEM	SYSTEM AND SERIES		Lithostratigraphic units of Love and others (1993)[1]	Hydrogeologic role/unit inferred from Berry (1955) [Cokeville area in the Overthrust Belt]	Hydrogeologic role/unit inferred from Robinove and Berry (1963) [Bear River valley in the Overthrust Belt]	Hydrogeologic role/unit inferred from groundwater potential evaluation of Wyoming Water Planning Program (1972, Table III-2)[2] [Snake and Salt River Basins]	Hydrogeologic divisions of Lines and Glass (1975, Sheet 1)[4] [Overthrust Belt]	Hydrogeologic role/unit of Ahern and others (1981, Figure II-7, Table IV-1, and text) [Overthrust Belt and Green River Basin]	Hydrogeologic unit of Blanchard (1990) and Blanchard and others (1990, p. 18) [Salt River Range]	Hydrogeologic unit of Glover (1990) [Bear River valley in Cokeville and Evanston areas in the Overthrust Belt]	Hydrogeologic unit of TriHydro Corporation (2002) [Cokeville area in the Overthrust Belt]	Hydrogeologic unit of Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) [All of Wyoming]	Hydrogeologic unit used in this report for Snake/Salt River Basin
CENOZOIC	QUATERNARY	Holocene	Alluvium and terrace deposits[1]	Local aquifers	Aquifers/local aquifers	Good aquifers	8–Quaternary sand and gravel	Major aquifers–Quaternary aquifers		Alluvial aquifer	Not discussed	Major aquifer–alluvial	Quaternary unconsolidated-deposit aquifers
		Pleistocene											
	TERTIARY	Pliocene	Salt Lake Formation; Camp Davis Formation		Not discussed/not defined or hydrogeologic characteristics unknown in investigators' study area at time of study	Not discussed; Fair to good aquifer	7–Tertiary conglomerate and tuffs	Major aquifer; Major aquifer		Not discussed or not present in investigator's study area		Major aquifer–sandstone; Marginal aquifer	Salt Lake aquifer; Camp Davis aquifer
		Miocene	Teewinot Formation			Poor aquifer		Major aquifer				Major aquifer	Teewinot aquifer
		Oligocene	Intrusive igneous rocks			Fair to poor aquifer	1–Igneous and metamorphic rocks	Not discussed				Marginal aquifer	Hydrogeologic role/unit not defined for study area
		Eocene	Conglomerate of Sublette Range; Wasatch Formation[2]	Potential aquifer	Not defined at time of study; Aquifer	Not discussed; Poor to fair aquifer	6–Tertiary siltstones and sandstones	Not discussed; Major aquifer		Wasatch aquifer		Not discussed; Major aquifer–sandstone	Wasatch aquifer
		Paleocene											
MESOZOIC	CRETACEOUS	Upper Cretaceous	Frontier Formation; Blind Bull Formation	Not discussed/not defined/not present or hydrogeologic characteristics unknown at time of study	Potential aquifer; Not discussed	Probable poor aquifer; Not discussed	5–Cretaceous shales and sandstones	Minor aquifer–Frontier aquifer; Not discussed		Not discussed or not present in investigator's study area		Minor aquifer; Not discussed	Frontier aquifer; Hydrogeologic role/unit not defined
			Sage Junction Formation; Wyam Formation: Quealy Formation; Aspen Shale		Not defined in investigators' study area at time of study; Probable confining unit	Not discussed; Not discussed; Confining unit		Not discussed/not defined in investigators' study area at time of study; Discontinuous aquifers with local confining units; Upper Jurassic-Lower Cretaceous aquifers: Minor aquifer	Discontinuous aquifers with local confining beds or locally utilized aquifer			Not discussed; Major aquitard	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined; Aspen confining unit
		Lower Cretaceous	Cokeville Formation; Thomas Fork Formation; Bear River Formation; Smiths Formation	Potential aquifer		Not discussed; Not discussed; Not discussed; Not discussed; Fair to poor aquifer					Thomas Fork Formation–aquifer		Marginal aquifer; Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined; Thomas Fork aquifer; Bear River aquifer; Hydrogeologic role/unit not defined
			Gannett Group: Smoot Formation; Draney Limestone; Bechler Conglomerate; Peterson Limestone; Ephraim Conglomerate		Potential aquifer	Fair to poor aquifer; Poor aquifer (?); Poor aquifer; Fair to poor aquifer (?); Fair to poor aquifer	4–Jurassic and Cretaceous sandstones and limestones			Not defined; Minor aquifer		Marginal aquifer	Gannett aquifer and confining unit
	JURASSIC	Upper Jurassic											
		Middle Jurassic	Stump Formation; Preuss Sandstone or Redbeds; Twin Creek Limestone		Potential aquifer; Potential aquifer; Potential aquifer	Fair to poor aquifer (?); Poor aquifer (?); Poor aquifer (?)		Aquitard (Figure II-7)/poor aquifer (Table IV-1); Minor aquifer		Not discussed or not present in investigator's study area		Minor aquifer; Minor aquifer; Minor aquifer	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined; Twin Creek aquifer
	JURASSIC (?) AND TRIASSIC (?)		Nugget Sandstone		Potential aquifer	Fair to good aquifer		Major aquifer		Minor aquifer		Major aquifer–sandstone	Nugget aquifer
	TRIASSIC	Upper Triassic	Ankareh Formation; Thaynes Limestone		Potential aquifer; Potential aquifer	Probable poor aquifer; Confining unit	3–Triassic and Permian siltstones and limestones	Minor aquifer/minor regional aquifer, locally confining; Major aquifer/regional aquifer: Nugget aquifer system		Not discussed or not present in investigator's study area		Not discussed; Minor aquifer; Marginal aquifer	Ankareh aquifer; Thaynes aquifer; Woodside confining unit
		Lower Triassic	Woodside Shale		Potential aquifer	Probable poor aquifer		Aquitard					
			Dinwoody Formation		Probable confining unit	Confining unit		Aquitard with locally productive zones				Marginal aquifer	Dinwoody aquifer and confining unit
PALEOZOIC	PERMIAN		Phosphoria Formation and related rocks		Potential aquifer	Poor aquifer		Minor aquifer–locally confining: Paleozoic aquifer system				Minor aquifer	Phosphoria aquifer and confining unit
	PENNSYLVANIAN	Upper Pennsylvanian	Wells Formation	Potential aquifer/good aquifer (identified as Tensleep Sandstone)	Potential aquifer	Probable poor to good aquifer	2–Paleozoic limestones and sandstones	Major aquifer (identified as Tensleep Sandstone on Figure II-7 and Wells Formation in text)		Minor aquifer	Not discussed	Major aquifer (identified as Tensleep Sandstone)–limestone	Wells aquifer
		Middle Pennsylvanian			Not discussed/not defined or hydrogeologic characteristics unknown in investigators' study area at time of study					Not discussed or not present in investigator's study area			
		Lower Pennsylvanian	Amsden Formation	Potential aquifer		Fair to poor aquifer		Minor aquifer–locally confining	Confining unit			Marginal aquifer	Amsden aquifer
	MISSISSIPPIAN	Upper Mississippian	Madison Group or Limestone	Potential aquifer/good aquifer		Fair to good aquifer		Major aquifer	Aquifer–Madison aquifer/subaquifer: Madison aquifer or aquifer system			Major aquifer–limestone	Madison aquifer
		Lower Mississippian											
	DEVONIAN	Upper Devonian	Darby Formation			Fair to poor aquifer		Major aquifer	Aquifer/subaquifer			Major aquifer–limestone	Darby aquifer
		Lower Devonian											
	SILURIAN	Upper and Middle Silurian											
	ORDOVICIAN	Upper Ordovician	Bighorn Dolomite	Not discussed/not defined/not present or hydrogeologic characteristics unknown at time of study		Fair to poor aquifer		Major aquifer	Aquifer/subaquifer			Major aquifer–limestone	Bighorn aquifer
		Middle Ordovician											
		Lower Ordovician											
	CAMBRIAN	Upper Cambrian	Gallatin Limestone			Probable poor aquifer		Minor aquifer	Aquifer/subaquifer			Minor aquifer	Gallatin aquifer
		Middle Cambrian	Gros Ventre Formation			Probable poor aquifer		Aquitard/regional aquitard	Confining unit			Minor aquifer	Gros Ventre aquifer and confining unit
			Flathead Sandstone			Poor to good aquifer		Minor aquifer–Flathead aquifer	Not discussed			Major aquifer–limestone[5]	Flathead aquifer
	PRECAMBRIAN		Precambrian rocks			Recharge areas	1–Igneous and metamorphic rocks	Minor aquifer–Precambrian aquifer				Major aquitard	Precambrian basal confining unit

[1]Alluvium and terrace deposits of Quaternary age not included in Love and others (1993).
[2]Includes main body Wasatch Formation, diamictite and sandstone, and Bullpen and Tunp Members.
[3]Poor aquifer is defined as potential well yield less than or equal to 50 gallons per minute (gal/min); fair aquifer is defined as potential well yield greater than 50 gal/min and less than or equal to 350 gal/min; and good aquifer is defined as potential well yield greater than 350 gal/min (Wyoming Water Planning Program, 1972, Table III-2, p. 60).
[4]Lithostratigraphic units grouped into eight hydrogeologic divisions based on "somewhat similar origins, lithologies, and water-bearing properties" (Lines and Glass, 1975, Sheet 1).
[5]Predominant lithology is sandstone, and it is unknown why formation is defined as "Major aquifer–limestone" in WWC Engineering and others (2007, Figure 4-9).

Plate 4. Relation of lithostratigraphic units to hydrogeologic units, Overthrust Belt, Snake/Salt River Basin, Wyoming.

ERATHEM	SYSTEM AND SERIES		Lithostratigraphic units of Love and others (1993)[1]	Hydrogeologic role/unit inferred from groundwater potential evaluation of Wyoming Water Planning Program (1972, Table III-2)[3] [Snake and Salt River Basins]	Hydrogeologic divisions of Lines and Glass (1975, Sheet 1)[4] [Overthrust Belt]	Hydrogeologic role/unit of Ahern and others (1981, Figure II-7, Table IV-1, and text) [Overthrust Belt and Green River Basin]	Hydrogeologic unit of Mills (1989) and Mills and Huntoon (1989) [eastern Gros Ventre Range]	Hydrogeologic unit of Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) [All of Wyoming]	Hydrogeologic unit of Bartos and Hallberg, (2010, Figures 5-2, 5-3, 5-4, text, and references therein) [Green River Basin]	Hydrogeologic unit of Bartos and others, (2012, Plate II, text, and references therein) [Wind River Basin]	Hydrogeologic unit used in this report for Snake/Salt River Basin
CENOZOIC	QUATERNARY	Holocene	Alluvium, terrace, and glacial deposits[1]	Good aquifers	8–Quaternary sand and gravel	Major aquifer–Quaternary aquifer	Not discussed	Major aquifer–alluvial	Quaternary aquifers/hydrogeologic units	Quaternary unconsolidated-deposit aquifers	Quaternary unconsolidated-deposit aquifers
		Pleistocene	Leidy Formation	Not discussed/not defined at time of study	7–Tertiary conglomerate and tuffs; Tertiary siltstones and sandstones	Not discussed/not present or not defined in investigators' study area at time of study		Not discussed	Not present in investigators' study area	Not discussed/not present in investigators' study area	Hydrogeologic role/unit not defined
	TERTIARY	Pliocene	Intrusive igneous rocks: Huckleberry Ridge Tuff; Shooting Iron Formation	Poor aquifer	1–Igneous and metamorphic rocks			Marginal aquifer: Not discussed; Not discussed			Quaternary and Tertiary volcanic rocks; Hydrogeologic role/unit not defined
		Miocene	Intrusive igneous rocks: Conant Creek Tuff; Camp Davis Formation; Teewinot Formation; Colter Formation	Poor aquifer; Fair to good aquifer; Fair to poor aquifer		Major aquifer; Major aquifer		Not discussed; Marginal aquifer; Major aquifer; Marginal aquifer			Quaternary and Tertiary volcanic rocks; Quaternary and Tertiary volcanic rocks: Camp Davis aquifer; Teewinot aquifer; Hydrogeologic role/unit not defined
		Oligocene	White River Formation	Not discussed				Marginal aquifer	White River aquifer	White River aquifer	White River aquifer
		Eocene	Intrusive igneous rocks	Poor aquifer	1–Igneous and metamorphic rocks			Marginal aquifer		Not discussed	Quaternary and Tertiary volcanic rocks
			Tepee Trail Formation	Not discussed	7–Tertiary conglomerate and tuffs; Tertiary siltstones and sandstones			Not discussed		Aycross–Wagon Bed confining unit	Hydrogeologic role/unit not defined
			Hominy Peak Formation; Aycross Formation	Not discussed				Not discussed; Not discussed		Not present; Aycross–Wagon Bed confining unit	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined
			Wind River Formation[2]	Poor to good aquifer				Major aquifer–sandstone		Wind River aquifer	Wind River aquifer
		Paleocene	Devils Basin Formation; Pinyon Conglomerate	Not discussed; Fair to poor aquifer				Not discussed		Hydrogeologic role/unit not defined; Meeteetse–Lewis confining unit	Hydrogeologic role/unit not defined
MESOZOIC	CRETACEOUS	Upper Cretaceous	Harebell Formation	Good aquifer	5–Cretaceous shales and sandstones; Jurassic and Cretaceous sandstones and limestones			Marginal aquifer			Hydrogeologic role/unit not defined
			Meeteetse Formation	Poor aquifer				Major aquitard			Meeteetse confining unit
			Mesaverde Formation	Poor aquifer		Major aquifer–Mesaverde aquifer		Minor aquifer	Mesaverde aquifer	Mesaverde aquifer	Mesaverde aquifer
			Sohare Formation	Not discussed		Not discussed/not present in investigators' study area		Marginal aquifer	Not present in investigators' study area	Not present in investigators' study area	Hydrogeologic role/unit not defined
			Bacon Ridge Sandstone	Good aquifer				Marginal aquifer			Hydrogeologic role/unit not defined
			Cody Shale; Frontier Formation	Poor aquifer; Probably poor aquifer		Minor aquifer		Major aquitard; Minor aquifer		Cody confining unit; Frontier aquifer and confining unit	Cody confining unit; Frontier aquifer
			Mowry Shale	Confining unit		Not discussed/not present in investigators' study area		Major aquitard	Baxter-Mowry confining unit	Mowry confining unit	Mowry confining unit
		Lower Cretaceous	Muddy Sandstone	Probably poor aquifer				Not discussed		Muddy Sandstone aquifer	Muddy Sandstone aquifer
			Thermopolis Shale	Confining unit				Major aquitard		Thermopolis confining unit	Thermopolis confining unit
			Cloverly Formation	Fair to poor aquifer				Minor aquifer	Cloverly aquifer	Cloverly aquifer	Cloverly aquifer
	JURASSIC	Upper Jurassic	Morrison Formation	Probably poor aquifer				Minor aquifer	Morrison confining unit	Morrison confining unit	Morrison confining unit
		Middle Jurassic	Sundance Formation	Poor aquifer (?)				Marginal aquifer	Sundance aquifer and confining unit	Sundance aquifer	Sundance aquifer
			Gypsum Spring Formation	Poor aquifer				Marginal aquifer	Gypsum Spring confining unit	Gypsum Spring confining unit	Gypsum Spring confining unit
	JURASSIC (?) AND TRIASSIC (?)		Nugget Sandstone	Fair to good aquifer		Major aquifer		Major aquifer–sandstone	Nugget aquifer	Nugget aquifer	Nugget aquifer
	TRIASSIC	Upper Triassic	Chugwater Formation	Fair to poor aquifer (?)	3–Triassic and Permian siltstones and limestones	Not discussed	Phosphoria-Dinwoody-Chugwater confining unit	Major aquitard	Chugwater-Dinwoody confining unit	Chugwater-Dinwoody confining unit	Chugwater aquifer and confining unit
		Lower Triassic	Dinwoody Formation	Confining unit		Aquitard with locally productive zones		Marginal aquifer			Dinwoody aquifer and confining unit
PALEOZOIC	PERMIAN		Phosphoria Formation and related rocks	Poor aquifer		Minor aquifer–locally confining		Minor aquifer		Phosphoria aquifer and confining unit	Phosphoria aquifer and confining unit
	PENNSYLVANIAN	Upper Pennsylvanian	Tensleep Sandstone	Poor to good aquifer	2–Paleozoic limestones and sandstones	Major aquifer	Tensleep aquifer (includes lower sandstones of Phosphoria Formation)	Major aquifer	Tensleep aquifer	Tensleep aquifer	Tensleep aquifer
		Middle Pennsylvanian; Lower Pennsylvanian	Amsden Formation	Fair to poor aquifer		Minor aquifer–locally confining	Amsden confining unit	Marginal aquifer	Amsden aquifer and(or) confining unit	Amsden aquifer	Amsden aquifer
	MISSISSIPPIAN	Upper Mississippian; Lower Mississippian	Madison Limestone	Fair to good aquifer		Major aquifer	Madison aquifer/subaquifer (Madison aquifer or aquifer system)	Major aquifer–limestone	Madison aquifer	Madison aquifer	Madison aquifer
	DEVONIAN	Upper Devonian	Darby Formation	Fair to poor aquifer		Major aquifer	Darby aquifer/subaquifer	Major aquifer–limestone	Darby confining unit	Darby aquifer	Darby aquifer
		Lower Devonian									
	SILURIAN	Upper and Middle Silurian									
	ORDOVICIAN	Upper Ordovician	Bighorn Dolomite	Fair to poor aquifer		Major aquifer	Bighorn aquifer/subaquifer	Major aquifer–limestone	Bighorn aquifer	Bighorn aquifer	Bighorn aquifer
		Middle Ordovician; Lower Ordovician									
	CAMBRIAN	Upper Cambrian	Gallatin Limestone; Gallatin Group: Snowy Range Formation; Pilgrim Limestone	Probably poor aquifer		Minor aquifer; Not discussed	Gallatin aquifer/subaquifer	Minor aquifer		Gallatin confining unit	Gallatin aquifer and confining unit
		Middle Cambrian	Gros Ventre Formation	Probably poor aquifer		Aquitard/regional aquitard	Park Shale confining unit; Death Canyon aquifer; Wolsey Shale confining unit	Minor aquifer	Gros Ventre confining unit	Gros Ventre confining unit	Gros Ventre aquifer and confining unit
			Flathead Sandstone	Poor to good aquifer		Minor aquifer–Flathead aquifer		Major aquifer–limestone[5]	Flathead aquifer	Flathead aquifer	Flathead aquifer
PRECAMBRIAN			Precambrian rocks	Recharge areas	1–Igneous and metamorphic rocks	Minor aquifer–Precambrian aquifer	Not discussed	Major aquitard	Precambrian basal confining unit	Precambrian basal confining unit	Precambrian basal confining unit

[1]Alluvium, terrace deposits, and glacial deposits of Quaternary age not included in Love and others (1993).
[2]Includes upper variegated sequence, coal sequence, and lower variegated sequence.
[3]Poor aquifer is defined as potential well yield less than or equal to 50 gallons per minute (gal/min); fair aquifer is defined as potential well yield greater than 50 gal/min and less than or equal to 350 gal/min; and good aquifer is defined as potential well yield greater than 350 gal/min (Wyoming Water Planning Program, 1972, Table III-2, p. 60).
[4]Lithostratigraphic units grouped into eight hydrogeologic divisions based on "somewhat similar origins, lithologies, and water-bearing properties" (Lines and Glass, 1975, Sheet 1).
[5]Predominant lithology is sandstone, and it is unknown why formation is defined as "Major aquifer–limestone" in WWC Engineering and others (2007, Figure 4-9).

Plate 5. Relation of lithostratigraphic units to hydrogeologic units, Teton and Gros Ventre Ranges, Snake/Salt River Basin, Wyoming.

ERATHEM	SYSTEM AND SERIES		Lithostratigraphic units of Love and others (1993)[1]		Hydrogeologic role/unit inferred from groundwater potential evaluation of Wyoming Water Planning Program (1972, Table III-2)[2] [Snake and Salt River Basins]		Hydrogeologic unit of Wyoming Framework Water Plan (WWC Engineering and others, 2007, Figure 4-9) [All of Wyoming]		Hydrogeologic unit of Bartos and others, 2012 (Plate II, text, and references therein) [Wind River Basin]		Hydrogeologic unit of Bartos and others, 2012 (Plate III, text, and references therein) [Bighorn Basin]		Hydrogeologic unit used in this report for Snake/Salt River Basin	
			A Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges	*A* Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges	*A* Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges	*A* Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges	*A* Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges	*A* Yellowstone Volcanic Area	*B* Absaroka and Washakie Ranges
CENOZOIC	QUATERNARY	Holocene	Sediments[1]	Alluvium, terrace, and glacial deposits[1]	Good aquifer		Major aquifer–alluvial		Quaternary unconsolidated-deposit aquifers		Quaternary unconsolidated-deposit aquifers		Quaternary unconsolidated-deposit aquifers	
		Pleistocene	Plateau Rhyolite: Osprey Basalt; Madison River Basalt; Basalts; Sediments interlayered with members of the Plateau Rhyolite	Basalt	Poor aquifer	Poor aquifer	Marginal aquifer	Marginal aquifer	Not discussed/not present in Wind River Basin	Not discussed/not present in Wind River Basin	Quaternary and Tertiary volcanic-rock aquifers		Quaternary and Tertiary volcanic rocks	
			Yellowstone Group: Lava Creek Tuff	Lava Creek B ash										
			Undine Falls Basalt											
			Mount Jackson Rhyolite											
			Sediments and basalts of the Narrows											
			Lewis Canyon Rhyolite											
			Yellowstone Group: Huckleberry Ridge Tuff											
	TERTIARY	Pliocene	Andesite, rhyolite, basalt, and gravel											
			Heart Lake conglomerate, intrusive rocks, and basalt	Basalt and vogesite										
			Conant Creek Tuff	? Caldwell Canyon Volcanics										
		Miocene	Colter Formation		Fair to poor aquifer		Marginal aquifer		Not discussed		Not discussed		Hydrogeologic role/unit not defined	
		Oligocene	White River Formation		Not discussed		Marginal aquifer		White River aquifer		White River aquifer		White River aquifer	
		Eocene		Intrusive igneous rocks	Poor aquifer				Not discussed/not present in Wind River Basin	Not discussed/not present in Wind River Basin	Quaternary and Tertiary volcanic rock aquifers (Absaroka Volcanic Supergroup aquifers)		Quaternary and Tertiary volcanic rocks	
			Intrusive igneous rocks; Absaroka Volcanic Supergroup: Thorofare Creek Group: Wiggins Formation											
			Thorofare Creek Group: Two Ocean Formation											
			Thorofare Creek Group: Langford Formation											
			Sunlight Group: Trout Peak Trachyandesite											
			Sunlight Group: Crescent Hill Basalt; Wapiti Formation	Tepee Trail Formation		Not discussed		Not discussed		Aycross-Wagon Bed confining unit		Not discussed		Hydrogeologic role/unit not defined
			Hominy Peak Formation	Aycross Formation		Not discussed		Not discussed		Aycross-Wagon Bed confining unit		Hydrogeologic role/unit not defined		Hydrogeologic role/unit not defined
			Washburn Group: Mount Wallace Formation; Lamar River Formation											
			Washburn Group: Sepulcher Formation; Cathedral Cliffs Formation											
				Crandall Conglomerate		Not discussed		Not discussed		Not discussed		Not discussed		Hydrogeologic role/unit not defined
				Wind River Formation		Poor to good aquifer		Major aquifer–sandstone		Wind River aquifer		Not discussed		Wind River aquifer
		Paleocene	Pinyon Conglomerate	Pinyon Conglomerate	Fair to poor aquifer	Fair to poor aquifer	Not discussed	Not discussed	Not discussed	Not discussed	Not discussed	Not discussed	Hydrogeologic role/unit not defined	
MESOZOIC	CRETACEOUS	Upper Cretaceous	Landslide Creek Formation; Harebell Formation	Cretaceous (?) intrusive igneous rocks; Harebell Formation	Poor aquifer (?); Good aquifer	Poor aquifer; Good aquifer	Marginal aquifer	Not discussed; Marginal aquifer	Not discussed; Not discussed	Not discussed; Not discussed	Not discussed; Not discussed	Not discussed; Not discussed	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined
				Mesaverde Formation		Poor aquifer		Minor aquifer						Mesaverde aquifer
			Everts Formation	Sohare Formation	Fair to poor aquifer (?)	Not discussed	Not discussed	Marginal aquifer	Not discussed		Not discussed		Hydrogeologic role/unit not defined	Hydrogeologic role/unit not defined
			Eagle Sandstone; Bacon Ridge Sandstone	Bacon Ridge Sandstone	Probably fair aquifer; Good aquifer	Good aquifer	Not discussed; Marginal aquifer	Marginal aquifer	Not discussed; Not discussed	Not discussed	Not discussed; Not discussed	Not discussed	Hydrogeologic role/unit not defined; Hydrogeologic role/unit not defined	
			Telegraph Creek Formation		Fair to poor aquifer		Not discussed		Not discussed		Not discussed		Hydrogeologic role/unit not defined	
			Cody Shale; Cody Shale	Cody Shale	Poor aquifer; Poor aquifer	Poor aquifer	Major aquitard; Major aquitard	Major aquitard	Cody confining unit; Cody confining unit	Cody confining unit	Cody confining unit; Cody confining unit	Cody confining unit	Cody confining unit	
			Frontier Formation; Frontier Formation	Frontier Formation	Probably poor aquifer; Probably poor aquifer	Probably poor aquifer	Minor aquifer; Minor aquifer	Minor aquifer	Frontier aquifer; Frontier aquifer	Frontier aquifer	Frontier aquifer; Frontier aquifer	Frontier aquifer	Frontier aquifer	
			Mowry Shale; Mowry Shale	Mowry Shale	Confining unit; Confining unit	Confining unit	Major aquitard; Major aquitard	Major aquitard	Mowry confining unit; Mowry confining unit	Mowry confining unit	Mowry confining unit; Mowry confining unit	Mowry confining unit	Mowry confining unit	
		Lower Cretaceous	Muddy Sandstone; Muddy Sandstone	Muddy Sandstone	Probably poor aquifer; Probably poor aquifer	Probably poor aquifer	Not discussed; Not discussed	Not discussed	Muddy Sandstone aquifer; Muddy Sandstone aquifer	Muddy Sandstone aquifer	Muddy Sandstone aquifer; Muddy Sandstone aquifer	Muddy Sandstone aquifer	Muddy Sandstone aquifer	
			Thermopolis Shale; Thermopolis Shale	Thermopolis Shale	Confining unit; Confining unit	Confining unit	Major aquitard; Major aquitard	Major aquitard	Thermopolis confining unit; Thermopolis confining unit	Thermopolis confining unit	Thermopolis confining unit; Thermopolis confining unit	Thermopolis confining unit	Thermopolis confining unit	
			Kootenai Formation; Cloverly Formation	Cloverly Formation	Fair to poor aquifer; Fair to poor aquifer	Fair to poor aquifer	Minor aquifer; Minor aquifer	Minor aquifer	Not discussed; Not discussed	Not discussed	Not discussed; Cloverly aquifer	Cloverly aquifer	Cloverly aquifer	
	JURASSIC	Upper Jurassic	Morrison Formation; Morrison Formation	Morrison Formation	Probably poor aquifer; Probably poor aquifer	Probably poor aquifer	Minor aquifer; Minor aquifer	Minor aquifer	Morrison confining unit; Morrison confining unit	Morrison confining unit	Morrison confining unit and aquifer; Morrison confining unit and aquifer	Morrison confining unit and aquifer	Morrison confining unit	
		Middle Jurassic	Ellis Group: Swift Formation; Sundance Formation	Sundance Formation	Fair to poor aquifer; Fair to poor aquifer	Fair to poor aquifer	Not discussed; Marginal aquifer	Marginal aquifer	Not discussed; Sundance aquifer	Sundance aquifer	Not discussed; Sundance confining unit and aquifer	Sundance confining unit and aquifer	Hydrogeologic role/unit not defined; Sundance aquifer	
			Ellis Group: Rierdon Formation		Confining unit									
			Ellis Group: Sawtooth Formation; Gypsum Spring Formation	Gypsum Spring Formation	Poor aquifer; Poor aquifer	Poor aquifer	Marginal aquifer	Marginal aquifer	Gypsum Spring confining unit	Gypsum Spring confining unit	Gypsum Spring confining unit and aquifer	Gypsum Spring confining unit and aquifer	Gypsum Spring confining unit	
	JURASSIC (?) AND TRIASSIC (?)			Nugget Sandstone		Fair to good aquifer		Major aquifer–sandstone		Nugget aquifer		Nugget aquifer		Nugget aquifer
	TRIASSIC	Upper Triassic	Chugwater Formation	Chugwater Formation	Fair to poor aquifer	Fair to poor aquifer	Marginal aquifer	Marginal aquifer	Chugwater aquifer and confining unit	Chugwater aquifer and confining unit	Chugwater aquifer	Chugwater aquifer	Chugwater aquifer and confining unit	
		Lower Triassic	Chugwater Formation; Chugwater Formation		Fair to poor aquifer; Fair to poor aquifer		Marginal aquifer; Marginal aquifer		Chugwater aquifer and confining unit; Chugwater aquifer and confining unit		Chugwater aquifer; Chugwater aquifer			
			Dinwoody Formation; Dinwoody Formation	Dinwoody Formation	Confining unit; Confining unit	Confining unit	Marginal aquifer; Marginal aquifer	Marginal aquifer	Dinwoody confining unit; Dinwoody confining unit	Dinwoody confining unit	Dinwoody confining unit; Dinwoody confining unit	Dinwoody confining unit	Dinwoody aquifer and confining unit	
PALEOZOIC	PERMIAN		Phosphoria Formation and related rocks; Phosphoria Formation and related rocks	Phosphoria Formation and related rocks	Poor aquifer; Poor aquifer	Poor aquifer	Minor aquifer; Minor aquifer	Minor aquifer	Phosphoria aquifer and confining unit; Phosphoria aquifer and confining unit	Phosphoria aquifer and confining unit	Phosphoria aquifer and confining unit; Phosphoria aquifer and confining unit	Phosphoria aquifer and confining unit	Phosphoria aquifer and confining unit	
	PENNSYLVANIAN	Upper Pennsylvanian												
		Middle Pennsylvanian	Quadrant Sandstone; Tensleep Sandstone	Tensleep Sandstone	Fair to poor aquifer (?); Poor to good aquifer	Poor to good aquifer	Not discussed; Major aquifer–limestone[3]	Major aquifer–limestone[3]	Not discussed; Tensleep aquifer	Tensleep aquifer	Not discussed; Tensleep aquifer	Tensleep aquifer	Tensleep aquifer	
		Lower Pennsylvanian	Amsden Formation; Amsden Formation	Amsden Formation	Fair to poor aquifer; Fair to poor aquifer	Fair to poor aquifer	Marginal aquifer; Marginal aquifer	Marginal aquifer	Amsden aquifer; Amsden aquifer	Amsden aquifer	Amsden confining unit; Amsden confining unit	Amsden confining unit	Amsden aquifer	
	MISSISSIPPIAN	Upper Mississippian												
		Lower Mississippian	Madison Group: Mission Canyon Limestone; Lodgepole Limestone; Madison Limestone	Madison Limestone	Fair to good aquifer; Fair to good aquifer	Fair to good aquifer	Major aquifer–limestone; Major aquifer–limestone	Major aquifer–limestone	Madison aquifer; Madison aquifer	Madison aquifer	Madison aquifer; Madison aquifer	Madison aquifer	Madison aquifer	
	DEVONIAN	Upper Devonian	Three Forks Formation; Darby Formation	Darby Formation	Confining unit; Fair to poor aquifer	Fair to poor aquifer	Major aquifer–limestone; Major aquifer–limestone	Major aquifer–limestone	Not discussed; Darby aquifer	Darby aquifer	Not discussed; Darby aquifer	Darby aquifer	Darby aquifer	
			Jefferson Formation		Fair to poor aquifer									
		Lower Devonian												
	SILURIAN	Upper and middle Silurian												
	ORDOVICIAN	Upper Ordovician	Bighorn Dolomite; Bighorn Dolomite	Bighorn Dolomite	Fair to poor aquifer; Fair to poor aquifer	Fair to poor aquifer	Major aquifer–limestone; Major aquifer–limestone	Major aquifer–limestone	Bighorn aquifer; Bighorn aquifer	Bighorn aquifer	Bighorn aquifer; Bighorn aquifer	Bighorn aquifer	Bighorn aquifer	
		Middle Ordovician												
		Lower Ordovician												
	CAMBRIAN	Upper Cambrian	Gallatin Group: Snowy Range Formation; Pilgrim Limestone; Gallatin Limestone	Gallatin Group: Snowy Range Formation; Pilgrim Limestone; Gallatin Limestone	Poor aquifer; Not discussed; Probably poor aquifer	Poor aquifer; Not discussed; Probably poor aquifer	Minor aquifer; Minor aquifer	Minor aquifer	Gallatin confining unit; Gallatin confining unit	Gallatin confining unit	Gallatin confining unit; Gallatin confining unit	Gallatin confining unit	Gallatin aquifer and confining unit	
		Middle Cambrian	Park Shale; Gros Ventre Formation	Gros Ventre Formation	Confining unit; Probably poor aquifer	Probably poor aquifer	Not discussed; Minor aquifer	Minor aquifer	Not discussed; Gros Ventre confining unit	Gros Ventre confining unit	Gros Ventre confining unit; Gros Ventre confining unit	Gros Ventre confining unit	Hydrogeologic role/unit not defined; Gros Ventre aquifer and confining unit	
			Meagher Limestone		Poor aquifer									
			Wolsey Shale		Confining unit									
			Flathead Sandstone; Flathead Sandstone	Flathead Sandstone	Poor to good aquifer; Poor to good aquifer	Poor to good aquifer	Major aquifer–sandstone; Major aquifer–sandstone	Major aquifer–sandstone	Flathead aquifer; Flathead aquifer	Flathead aquifer	Flathead aquifer; Flathead aquifer	Flathead aquifer	Flathead aquifer	
PRECAMBRIAN			Precambrian rocks; Precambrian rocks	Precambrian rocks	Recharge areas; Recharge areas	Recharge areas	Major aquitard; Major aquitard	Major aquitard	Precambrian basal confining unit; Precambrian basal confining unit	Precambrian basal confining unit	Precambrian basal confining unit; Precambrian basal confining unit	Precambrian basal confining unit	Precambrian basal confining unit	

[1]Alluvium, terrace deposits, and glacial deposits of Quaternary age not included in Love and others (1993). Includes deposits of Holocene and Pleistocene age.
[2]Poor aquifer is defined as potential well yield less than or equal to 50 gallons per minute (gal/min); fair aquifer is defined as potential well yield greater than 50 gal/min and less than or equal to 350 gal/min; and good aquifer is defined as potential well yield greater than 350 gal/min (Wyoming Water Planning Program, 1972, Table III-2, p. 60).
[3]Predominant lithology is sandstone, and it is unknown why formation is defined as "Major aquifer–limestone" in WWC Engineering and others (2007, Figure 4-9).

Plate 6. Relation of lithostratigraphic units to hydrogeologic units, Yellowstone Volcanic Area and Absaroka and Washakie Ranges, Snake/Salt River Basin, Wyoming.

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