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

Wind/Bighorn River Basin Water Plan Update Groundwater Study Level I (2008–2011)

Available Groundwater Determination Technical Memorandum

by

Paul Taucher, Timothy T. Bartos, Keith E. Clarey, Scott A. Quillinan, Laura L. Hallberg, Melanie L. Clark, Melissa Thompson, Nikolaus Gribb, Brett Worman, and Tomas Gracias

Prepared for the Wyoming Water Development Commission

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Cover: Outcrop of Triassic Chugwater Formation on Red Gulch Road southeast of Shell, on the eastern flank of the Bighorn Basin. Composed primarily of red siltstone and shale of the Red Peak Shale Member. Outcrop is capped by the thin limestone of the Alcova Limestone Member. Crow Mountain Sandstone Member can serve as reservoir rock where present. Photo by Alan J. Ver Ploeg (2005).

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WWDC Wind/Bighorn River Basin Water Plan Update –
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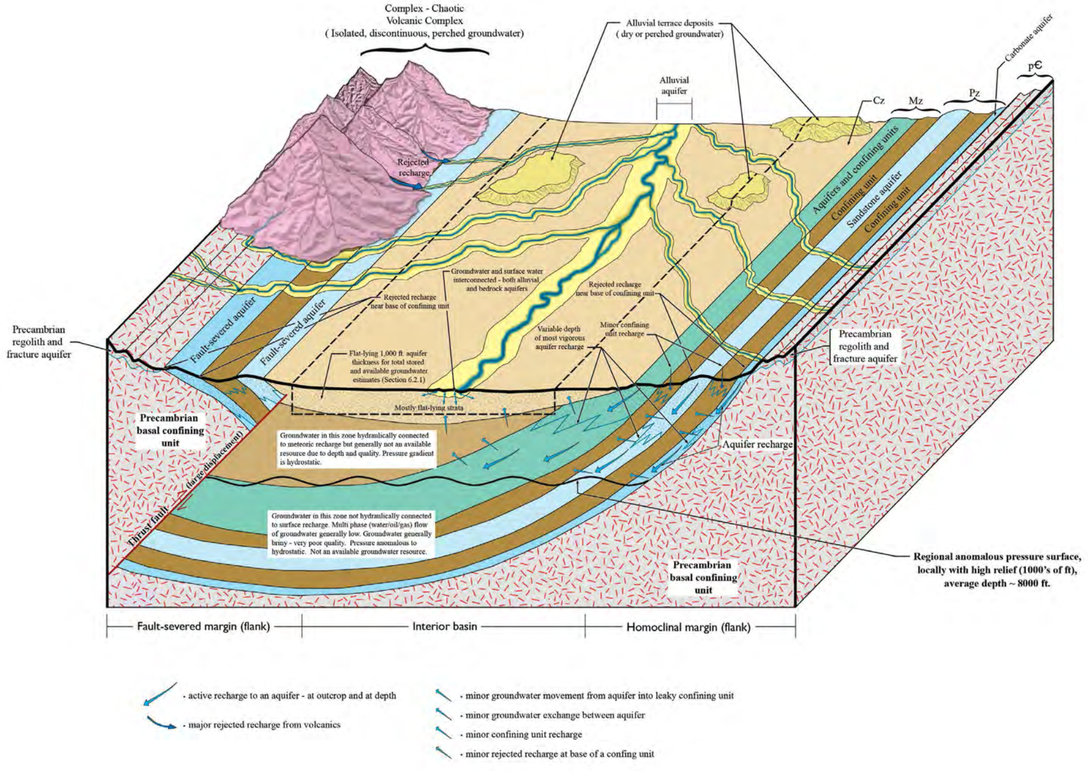
List of Acronyms

AMCL	alternative MCL
AML	abandoned mine land
AMLE	adjusted maximum likelihood estimation
ANC	acid-neutralizing capacity
AYV	Absaroka and Yellowstone Volcanic Area
BAG	Basin Advisory Group
BCGS	basin-centered gas system
BHB	Bighorn Basin
BIA	Bureau of Indian Affairs
BUREC	U.S. Bureau of Reclamation
CAFO	concentrated animal feeding operation [feedlot]
CBNG	coalbed natural gas
EA	Environmental Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency (U.S.)
ET	evapotranspiration
FS	Forest Service (U.S.)
GIS	geographic information system
GPS	global positioning system
HAL	health advisory level
ICP	independent cleanup process
LQD	Land Quality Division (WDEQ)
MBMG	Montana Bureau of Mines and Geology
MCL	maximum contaminant level
MDL	multiple detection limit
MGIC	Montana Geographic Information Clearinghouse
NPDES	National Pollutant Discharge Elimination System (USEPA)
NWIS	National Water Information System (USGS)
PLSS	Public Land Survey System
POTW	public owned treatment works
PWD	Produced Waters Database (USGS)
RCRA	Resource Conservation and Recovery Act
RMLB	Rocky Mountain Laramide basin
R/P	recharge/precipitation ratio; recharge fraction (of precipitation)
SAR	sodium-adsorption ratio
SC	Statement of Completion
SDVC	Spatial Data and Visualization Center (UW – now WyGISC)
SDWA	Safe Drinking Water Act
SHWD	Solid and Hazardous Waste Division (WDEQ)
SMCL	secondary maximum contaminant level
SWAP	Source Water Assessment Program
TDS	total dissolved solids
TSD	treatment storage and disposal
UCG	underground coal gasification
UIC	underground injection control
USBLM	U.S. Bureau of Land Management

USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UW	University of Wyoming
VRP	Volunteer Remediation Program
WBRB	Wind/Bighorn River Basin
WDA	Wyoming Department of Agriculture
WDEQ	Wyoming Department of Environmental Quality
WOGCC	Wyoming Oil & Gas Conservation Commission
WQD	Water Quality Division (WDEQ)
WRB	Wind River Basin
WRDS	Water Resources Data System (University of Wyoming)
WRRI	Water Resources Research Institute (University of Wyoming)
WSEO	Wyoming State Engineer's Office
WSGS	Wyoming State Geological Survey
WWDC	Wyoming Water Development Commission
WWDO	Wyoming Water Development Office
WyGISC	Wyoming Geographical Information Science Center (UW – was SDVC)
WYPDES	Wyoming Pollutant Discharge Elimination System

Frontispiece. Conceptual block diagram of WBRB groundwater regime that illustrates various hydrogeologic concepts discussed in this memorandum, including:

- Paleozoic through Quaternary sedimentary geologic units progressively deposited on the Precambrian basement and subsequently folded, faulted, and eroded to form the current hydrogeologic framework of a structural groundwater basin
- Outcrop areas of various hydrogeologic units, where recharge infiltrates to the subsurface
- Typical settings for rejected recharge
- A thick pile of volcanic material deposited on an evolving landscape during the Tertiary
- A deep basin volume of rocks where development of multi-phase (hydrocarbons, water, gas) conditions substantially restricts groundwater flow
- The volume of the Q/T Aquifer that was the basis of stored and available groundwater estimates
- A depiction of the Quaternary Aquifer – deposited on rocks ranging in age from Precambrian to Tertiary – that was also the basis of stored and available groundwater estimates
- The exchange of groundwater between Quaternary and underlying hydrogeologic units



Chapter 1
Introduction

Paul Taucher
Scott Quillinan
Keith Clarey

Part 1– scope, participating agencies, and legal framework

In 1973 the Wyoming State Engineer's Office (WSEO) compiled the first State Framework Water Plan. In 1979, the Wyoming State Legislature created the Wyoming Water Development Commission (WWDC) to coordinate water and related land resources planning for the state. Between 1979 and 1995, the WWDC completed several major river basin planning studies. In 1996 the Legislature directed WWDC to conduct a Water Planning Feasibility Study. On the basis of results of the feasibility study the Legislature funded the Statewide Water Planning Process in 1999 to update the original 1973 State Framework Water Plan, and specifically to:

- Inventory the state's water resources and related lands
- Summarize the state's present water uses and project future water needs.
- Identify alternatives to meet projected future water needs.
- Provide water resource planning direction to the State of Wyoming for a 30-year time-frame.

The resulting Wyoming Framework Water Plan (WWC Engineering, 2007) summarized the seven separate river basin plans for Wyoming's seven major drainage basins **(Figure 1-1)** compiled between 2001 and 2006 for the WWDC. The Wind/Bighorn River Basin plan (BRS Inc., 2003e) summarized several technical memoranda, including the initial Available Groundwater Determination for the Wind/Bighorn River Basin Technical Memorandum (Lidstone and Associates, Inc., 2003).

The present Available Groundwater Determination Technical Memorandum updates the 2003 Technical Memorandum; it will inform revisions of the 2003 Wind/Bighorn River Basin Plan and the 2007 Wyoming Framework Water Plan. It presents a new compilation of available information on the groundwater resources of the WBRB. While original maps and tables were developed for this memorandum, no original investigations were performed.

1.1 Scope

The WWDC and the Wyoming State Geological Survey (WSGS) entered into an Interagency Agreement in June 2008 to review and compile existing information to update the 2003 Available Groundwater Determination Technical Memorandum (Lidstone and Associates, Inc., 2003). A downloadable file containing the 2003 Memorandum is available online at the WWDC website,

http://wwdc.state.wy.us under River Basin Planning.

The scope of the project is as follows:

- Identify the major (most heavily used) aquifers in the WBRB.
- Describe the three-dimensional extent of the hydrogeologic units.
- Describe the physical properties of the lithostratigraphic units and the physical properties and chemical characteristics of the groundwater in the hydrogeologic units.
- Describe the aquifer recharge areas.
- Estimate aquifer recharge rates.
- Estimate total and available quantities of the water in the aquifers.
- Estimate "safe yield" potential for the aquifers.
- Describe areas where groundwater development may impact surface water use and areas of interference between aquifers.Discuss future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands.

1.2 Agency participation, responsibilities, and oversight

This report is the result of a cooperative effort by the WWDC/WWDO, WSGS, the U.S. Geological Survey (USGS), and Wyoming Water Resources Data System (WRDS). The WSEO and the WDEQ contributed significant resources for developing some of the data presented in this report.

- The WWDO and WRDS provided the WSGS with overall program guidance and standards, software, and format requirements for deliverables (maps, databases, metadata, tables, graphs, etc.).
- The WSGS was the primary compiler of the deliverables associated with Chapter 6 and of the maps and databases for presenting available data on wells and springs.
- The USGS, under contract to the WSGS, was the compiler of the deliverables associated with Chapter 7, and with Section 5.6.1.
- The WSGS and USGS cooperated on sections of Chapters 5, 6, 8, and 9.
- The WRDS aided the WSGS with the hard copies of the final report for this project, and hosts the report and associated deliverables on the Internet on behalf of WWDC/WWDO.

The USGS provides maps, reports, and other information to help states meet their needs to manage, develop, and protect America's water, energy, mineral, and land resources. The USGS was a primary developer and contributor of the groundwater information provided in this Technical Memorandum.

The Wyoming Water Resources Data System (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 WRDS assisted in the development and presentation of the State Water Plan and this Technical Memorandum.

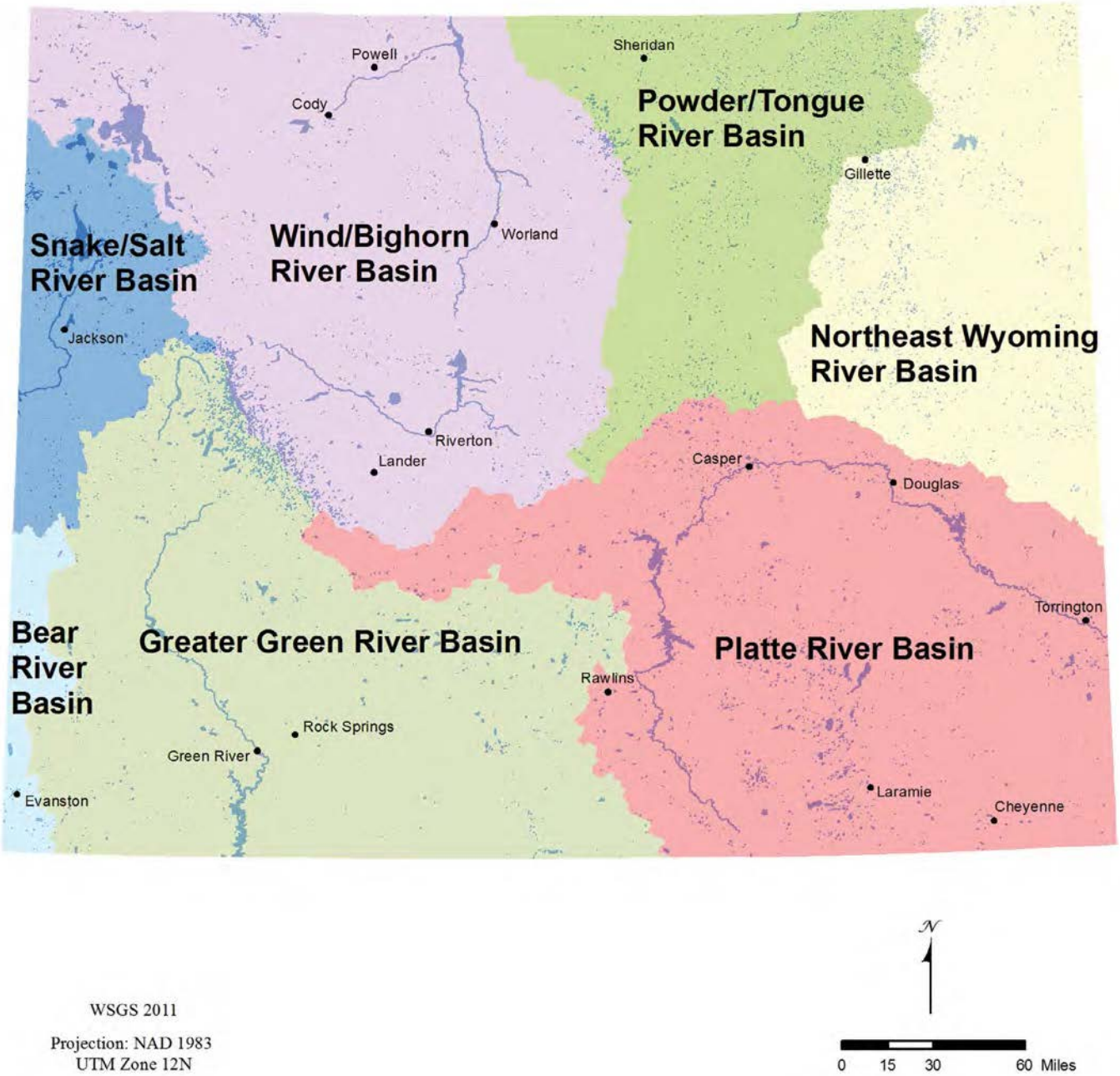


Figure 1-1. Major drainage basins, Wyoming.

The Wyoming Water Development Commission (WWDC) is the water development planning agency for Wyoming. They administer new public-funded development, construction, rehabilitation, and related groundwater studies. WWDC programs are administered primarily by the Wyoming Water Development Office (WWDO).

The Wyoming State Engineer's Office (WSEO) and WWDO cooperate on many projects. WSEO personnel coordinate river-basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the WSEO and WDEQ (Pers. Comm., Keith Clarey, WWDO).

The U.S. Bureau of Reclamation (BuRec), an agency under the U.S. Department of the Interior, oversees and manages water resources specifically related to the operation of numerous water diversion, delivery, storage, and hydroelectric power generation projects built by the federal government throughout the western United States. The U.S. BuRec cooperates with the WSEO and the WWDC (primarily with the WSEO), but as a federal agency may execute some programs unilaterally. The BuRec coordinates releases from Wyoming's reservoirs with the WSEO. (Pers. Comm., Keith Clarey, WWDO). Agencies with oversight over groundwater quality are described below in Sections 1.3.2. and 5.6.1.

1.3 Legal authority

Wyoming laws that govern the appropriation, development, and beneficial use of water resources are based on the doctrine of prior appropriation, commonly stated as *"first in time is first in right."* This means that the first party to put a source of water to beneficial use has a "priority" water-right that will be honored prior to those of other users with later water-rights during periods of limited supply. An exception is that municipalities can obtain water-rights from earlier priority uses through eminent domain under specific conditions. Because all waters within Wyoming are property of the State, a water-right does not grant ownership, but only the right to use water for beneficial purposes. Use of water resources for domestic and livestock purposes customarily take precedence over other uses. In Wyoming, water-rights are attached to the land and can be transferred. The laws and regulations pertaining to the appropriation, development, and beneficial use of groundwater are administered by the WSEO and a Board of Control made up of the superintendents of the four state water divisions and the State Engineer. The entire WBRB is included in Water Division III. Comprehensive discussion of the laws that govern all Wyoming water resources is provided in the main updated Wind/Bighorn River Basin Water Plan (MWH, 2010) and online at

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

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

Groundwater within the state is owned and controlled by the State of Wyoming. Under Wyoming law, groundwater includes any water (including geothermal waters) under the land surface or under the bed of any body of surface water. The WSEO is responsible for the permitting and orderly development of groundwater in Wyoming. The updated WBRB Water Plan (MWH, 2010) provides the following discussion of Wyoming water law specific to groundwater:

> "Wyoming's groundwater laws were originally enacted in 1945 and amended in 1947. These laws were replaced by new groundwater laws on March 1, 1958, which were then amended in 1969. Groundwater is administered on a permit basis. The acquisition of groundwater rights generally follows the same permitting procedures as surface water rights, except that a map is not required at the time of permit application. Applications are submitted to and approved by the WSEO prior to drilling a well. With the completion of the well and application of the water to a beneficial use, the appropriation can then be adjudicated. The issuance of well permits carries no guarantee of a continued water level or artesian pressure."
>
> "As with surface water rights, groundwater rights are administered on a priority basis. For all wells drilled prior to April 1, 1947, a statement of claim process was followed to determine the priority date of the well. For wells drilled between April 1, 1947 and March 1, 1958, the priority date is the date the well was registered. For wells drilled after March 1, 1958, the priority date is the date the application was received at the WSEO."
>
> "Domestic and stock wells are those wells used for non-commercial household use, including lawn and garden watering that does not exceed one acre in aerial extent, and the watering of stock. The yield from these wells cannot exceed 25 gallons per minute (gpm). 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 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."

The potential for interconnection between groundwater and surface water is presently a prominent water-rights issue in

the Platte River Basin and is of increasing concern throughout Wyoming. Surface flows are generally subject to strict water rights, and conflicts among users within the state or across state lines may arise where groundwater extraction can affect surface flows.

1.3.2 Wyoming water law – groundwater quality

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

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

and on the WWDC website.

Except on the Wind River Indian Reservation, The Wyoming Department of Environmental Quality (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 & Gas Conservation Commission and the U.S. Bureau of Land Management (or the EPA or U.S. Forest Service) that cause groundwater contamination are referred to the WDEQ; the WOGCC and BLM have jurisdiction over Class II underground injection wells dedicated to disposal of produced water from state and federal oil-and-gas leases, respectively. Groundwater quality issues on the Reservation are generally referred to the EPA and BLM, with potential involvement of the Wind River Environmental Quality Council or the Bureau of Indian Affairs.

1.3.3 Interstate agreements

As established by the Wyoming state constitution, all surface water and groundwater within Wyoming's borders is property of the state. However, surface water in the various river basins is subject to interstate river basin compacts that limit the depletion of stream flow within Wyoming. While most compacts do not include groundwater, the interstate nature of groundwater resources along state lines and where groundwater interconnects with surface water is recognized by Wyoming agencies involved with groundwater. Like surface water, groundwater is shared with Wyoming's neighbors; groundwater development near state borders must take water-resources agreements into account.

1.4 Authorship

The principal authors of this report were

Paul Taucher, Energy Compliance LLC, Laramie, Timothy T. Bartos, U.S. Geological Survey, Wyoming Water Science Center, Cheyenne, and the Wyoming State Geological Survey, Laramie.

1.5 Acknowledgements

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The Wyoming State Engineer's Office (WSEO) provided groundwater permit data for Wyoming. We would like to express gratitude specifically to Jeremy Manley and Nancy McCann at the WSEO for many data transfers, phone calls, and quality control checks. The Wyoming Oil and Gas Commission (WOGCC), Casper, specifically Rick Marvel and Robert Meyer, compiled and provided a produced-water-quality dataset for the study area. The Wyoming Department of Environmental Quality (WDEQ) contributed several datasets that are presented on the potential aquifer contaminant figures. Special thanks are expressed to Chad Kopplin, Ben Way, Adrienne Nunn, Bill DiRienzo, Marica Murdock, Bonnie Pierce, Kim Medina, and many other, unnamed folks at the WDEQ. Jeff Hammerlink from the Wyoming Geographic Information Science Center (WyGisc) provided the data used to describe aquifer sensitivity and recharge.

Past State Geologists Ronald Surdam and Wallace Ulrich provided guidance and support throughout the project. Map editing and direction was provided by Richard "Dick" Jones, P.G., WSGS map editor. We thank Keith Clarey, WWDO: he compiled Appendix A, made major contributions to chapters 5 and 8, and answered many questions. Immense gratitude is expressed to document and map editor David Copeland, who through many hours of dedication greatly improved the quality of the work presented in this document, and to Brett Worman for his perspicacious editorial assistance. We recognize Chamois Andersen for document preparation and layout. Tomas Gracias, Brett Worman, Robin Lyons, Phyllis Ranz, and J. Fred McLaughlin at the WSGS provided appreciable help. At the WSGS, Nik Gribb did the digital cartography for Plates I, IV, and V; Tomas Gracias did layout and digital work for Plates VII and VIII; Allory Deiss designed Figure 6-1 and solved problems on many other WSGS figures; Melissa Thompson designed and produced nearly all WSGS figures for this report;

and Richard Hays culled through several consulting reports to provide Appendix B. Suzanne Roberts, USGS illustrator, generated Plates XII, XIII, and XIV; figures in chapter 7; and Appendices E–H.

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

Part 2– WBRB groundwater regime

1.6 Basis of this groundwater assessment

Because the assessment of groundwater resources on a basin-wide scale is data limited, the approach in this study was to develop a conceptual model of the overall hydrogeologic system based on available data and the findings of previous studies. The various methods commonly used by hydrogeologists and groundwater engineers to define specific groundwater development prospects were scaled-up, and very general assumptions were utilized, to characterize a hypothetical basin-wide resource **(Section 6.2)**. The lack of the data that would be required to provide a comprehensive basin-wide evaluation of any single aquifer or area limits the level of detail that can be applied to specific development prospects. In most cases hydrogeologic and hydrogeochemical data available for areas that have not already been developed are sparse. While this study provides a summary of available information and general guidance on the groundwater resource potential of the WBRB, new development of groundwater in sufficient and sustainable quantities and quality to meet supply requirements will require some degree of site-specific hydrogeologic investigation and analyses. We discuss in Chapter 9 the few site-specific, aquifer-specific, and project-specific development prospects that we are able to distinguish.

Coauthors who contributed to the various chapters were	
Keith Clarey, WWDO	Laura Hallberg, USGS
Melanie Clark, USGS	Scott Quillinan, WSGS
Tomas Gracias, WSGS	Melissa Thompson, WSGS
Nikolaus Gribb, WSGS	Brett Worman, WSGS

The feasibility of developing groundwater to meet large-volume supply requirements (e.g. municipal, industrial, agricultural) depends on a favorable coincidence of several factors:

- A demand for the groundwater resource – any aquifer (by definition) and some water-bearing units that are not classified as aquifers (confining units) could provide useful groundwater supplies should sufficient demand exist
- Water quantity and quality that meet the requirements of the project
- Recharge conditions and hydrogeologic characteristics of the prospect aquifer(s) that could sustain production
- Amenable legal, institutional, and cultural conditions (water rights, land ownership, point of use relative to location of the resource, pipeline right-of-way, accessibility of drilling location, etc.)
- Funding adequate to properly develop the resource

Optimum conditions for the development of large-volume groundwater supplies are realized when all of the above favorable hydrogeologic and non-technical factors exist. None of the aquifers identified in this study are accessible throughout the WBRB, nor can they be expected to produce water in sufficient quantity and quality to meet demand requirements in all locations where they are accessible. In some areas, useable groundwater resources are not available.

1.7 Hydrogeology

Plates II, III, and IV outline the hydrogeologic units present in the WBRB. **Plate IV** is a map of the surface hydrogeology of the WBRB, the outcrop areas of identified aquifers and confining units. It includes near-surface structures that affect the occurrence and flow of groundwater. The frontispiece and Figure 5-0 are conceptual diagrams of a typical Rocky Mountain Laramide basin (basin formed during the Late Cretaceous-early Tertiary Laramide Orogeny) that illustrate the groundwater resource concepts and information presented in this study.

Because recharge occurs primarily in *aquifer outcrop areas*, groundwater in these areas is shallowest and of the best quality. Paleozoic and Mesozoic aquifers that crop out in the mountain ranges and foothills around the margins of the Wind River and Bighorn basins dip beneath younger formations into the structural basins, and groundwater tends to flow from these recharge areas downdip into the basins to the extent permitted by favorable hydraulic characteristics and continuity. The entire thickness of the Paleozoic and Mesozoic geologic section is commonly exposed in upland areas surrounding the basins. Recharge is more efficient where infiltration and percolation occurs parallel to bedding, generally the direction of highest permeability. Where favorable conditions prevail, good-quality groundwater can be available from productive basin-margin aquifers for several miles basinward of their outcrop areas (at increasing depth). Unconfined conditions generally prevail in outcrop areas. Where an aquifer is overlain by less-permeable strata, confined conditions prevail. The Paleozoic and Mesozoic aquifers are present beneath essentially the entire basin; however, in the absence of favorable structures, the prospects for development diminish as depth increases basinward, along with increasing costs of exploration and production, declining water quality, and in some cases declining permeability (e.g., carbonate aquifers and cementation).

As discussed in **Section 5.4**, except in the Quaternary alluvial and relatively flat-lying Tertiary bedrock aquifers, geologic

structure (folds and faults) can be an important or controlling factor in developing groundwater resources, especially in the more structurally complex mountain and foothill areas that surround the basins. Shallow large-scale structures are rare and, therefore, much less important in the basin interiors. In the soluble carbonate (limestone and dolomite) aquifers, groundwater circulation within faults and fractures increases pore size and permeability, sometimes as expressed dramatically in the formation of cave systems, but mostly at smaller scales. Where the Paleozoic carbonate aquifers are characterized by highly productive karstic transmissivity, their recharge areas in the uplands around the perimeter of the basins are well-connected with the deeper basins, and groundwater circulation is relatively vigorous; useable groundwater resources, in terms of both quantity and quality, can be available some distance from the outcrop areas, although at greater depth than normally expected.

Aquifers exposed in the interior lowlands of both structural basins are primarily Quaternary alluvial and lower Tertiary hydrogeologic units. Recharge to unconsolidated alluvial aquifers from precipitation and irrigation is effective, even across bedding, except where erosion has exposed the strata of Tertiary bedrock units; recharge to these units occurs mostly across bedding, generally the direction of lowest permeability. Most recharge to, and the highest yields from, both Quaternary and Tertiary aquifers occurs in areas adjacent to active streams and areas under irrigation. The alluvial aquifers are not evenly distributed, and the bedrock aquifers were deposited in fluvial environments; the result is a lenticular distribution of the sand and gravel lithologies that are most favorable for groundwater development. Unconfined conditions generally prevail in alluvial and shallow bedrock aquifers, and progressively confined conditions are encountered with depth in the bedrock aquifers. Because the interior areas of the basins are generally accessible, the technical potential for developing mid- to high-yield groundwater resources in this setting depends primarily on a spatially variable combination of recharge and favorable aquifer characteristics. The level of recharge in the interior basins is generally lower than in the surrounding foothills and mountains; nevertheless, useful groundwater resources can be found at most locations but may be adequate only for low-yield uses (e.g., rural domestic and stock). The widespread occurrence of shallow groundwater confirms the conservative estimates for recharge in the interior basin areas proposed in the analysis presented in **Section 6.2.2**. Fractures, especially in areas where they are associated with the course of a surface drainage, may also play a role in the recharge of the lower Tertiary aquifers, but not to the extent that fractures are associated with groundwater resources in the Paleozoic carbonate aquifers.

As discussed in **Section 5.1**, because unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than will confined aquifers, unconfined aquifers are generally more attractive prospects for development. In interior basin areas, unconfined aquifers are widely exposed and can be recharged over a much larger area than confined aquifers. Unconfined aquifers are at shallower depth, and therefore are easier and substantially less costly to investigate and develop. The generally shallow depth of unconfined aquifers and their lack of a protective overlying confining layer also present the disadvantage of being vulnerable to contamination from a variety of sources (**Section 5.7**).

1.8 Current and historic groundwater development and use patterns

Current and historic groundwater development and use patterns are important considerations in evaluating an area's potential for groundwater development, and may be adequate for shallow, low- to mid-range (mostly stock and domestic use) yields; however, evaluation and development of an area's potential for deeper, high-range sustainable flows for municipal, industrial, and irrigation uses may vary significantly from historic patterns. Factors that change historic development patterns are technical (e.g., better understanding of local hydrogeology, improved drilling and treatment technologies) or cultural (e.g., changes in surface development, land ownership, demand).

Historic development patterns reflect both favorable hydrogeologic conditions and demand. There are areas where groundwater is available but population is inadequate to justify development. There are areas where low yield and marginal groundwater quality is the only option to meet demand. And there are areas where the conditions that have concentrated population are coincident with optimal conditions for groundwater development; for example, where communities develop on the alluvial plain surrounding a major river.

The best general settings for groundwater development in the WBRB have been identified for many years and are reflected in where drilling has occurred over the last and during the current century **(Plate IV)**. WWC Engineering et al. (2007b) reported that groundwater yields of less than 5 gpm are widely available throughout Wyoming. Yields ranging from 5 to 50 gpm are generally available from most of the "major aquifers" identified in this study. Yields greater than 50 gpm generally require favorable local hydrogeologic conditions. In general, groundwater availability is greatest within specific areas of the alluvial aquifers in both basins, and to a lesser extent within the lower Tertiary bedrock aquifer in the Wind River Basin. **Plates IV and X** show that most groundwater permits in the WBRB have been issued within the interior basin areas, where Quaternary alluvial and Tertiary bedrock aquifers provide groundwater supplies for a variety of uses over a wide range of permitted yield. Current yields of 1,000 gpm or more are only available from specific areas of highly productive alluvial, lower Tertiary bedrock, and Paleozoic carbonate aquifers (primarily the Madison–Bighorn aquifer). The Paleozoic

aquifers have potential for developing high-yield wells adjacent to and downgradient from their recharge areas exposed in the mountain ranges surrounding the structural basins that is highly dependent on local hydrogeologic conditions.

Figure 5 in the Executive Summary of the WWDC 2003 WBRB Water Plan (BRS, Inc et al., 2003b) mapped several areas potentially favorable for new and additional groundwater development in the WBRB, based on hydrogeology and historic development patterns, including:

- the Quaternary alluvial aquifers of both groundwater basins
- areas where structure (fractures) and dissolution have potentially enhanced the permeability of the Paleozoic carbonate aquifers in both groundwater basins
- the Lower Tertiary aquifer in the Wind River Basin

These prospective areas are shown on **Plate X** in relation to surface hydrogeology mapped as outcrop areas of hydrogeologic units, major faults, and other lineaments. Information on groundwater permits issued since 2000 including locations, depths, and yields (by well symbol); tabulation of depth vs. yield; and charts depicting summary statistics for well use and average depth by use are also included in **Plate X** to illustrate how development in the WBRB has proceeded since the "Potential Areas of Future Ground Water Development" prediction was presented in the 2003 WBRB water plan. Comparison of **Plate IV** (all groundwater permits in the WBRB) with **Plate X** shows that groundwater development since 2000 has continued historic trends, and that permits have been located in the outcrop areas of most hydrogeologic units identified in the WBRB, including confining units, ranging from Quaternary through Precambrian, both within and outside the "Potential Areas" identified in 2003.

1.8.1 Alluvial aquifer potential groundwater areas

Most groundwater permits issued for the WBRB, both through 2009 and from 2000 through 2009 have been in areas underlain by the alluvial aquifers near major drainages where the alluvial aquifer has been historically developed, both within and outside of the "Potential Areas …" identified in 2003. **Plate IV** shows, and the **Chapter 8** discussion on historical development indicates, that of all groundwater permits to date, most by far have been issued for areas underlain by alluvial aquifers. **Figures 8-2, 8-7, and 8-9** for Domestic, Stock, and Miscellaneous permits, show that most of these permits are for relatively low production (25 gpm or less) and for depths of 500 feet or less. That a substantial fraction of the wells permitted within areas underlain by alluvial aquifers were for depths (50 to 500 feet) that generally exceed alluvial thickness indicates that many of these wells were completed within lower Tertiary aquifers, and that cultural factors related to surface development along major drainages may have played a significant role in where development occurred. It is not apparent that the 2003 designation of the alluvial aquifers prospective areas had an effect on historical development patterns for low-yield groundwater resources.

The 2003 "Potential Areas of Future Ground Water Development" did not identify an area for future potential development within the interior Bighorn Basin in either the Tertiary or Quaternary alluvial aquifers. Nevertheless, there was a substantial amount of groundwater permitting, both before and after 2000, in interior basin areas underlain by alluvial aquifers. Both **Plates IV and X** show that there has been very little development where the Tertiary bedrock aquifers are exposed in the interior Bighorn Basin; this low level of development reflects both less favorable hydrogeologic conditions in the Willwood and Fort Union aquifers and lack of demand outside of the areas surrounding the major drainages of the basin.

1.8.2 Tertiary aquifer potential groundwater areas

A large area for future groundwater development within the lower Tertiary aquifers in the Wind River Basin is outlined in "Potential Areas of Future Ground Water Development" (BRS, Inc., 2003b). In several cases, wells are clearly permitted in areas where the Tertiary aquifers are exposed; however, as discussed above, a substantial number of wells permitted for lower yields and at depths ranging from 50 to 500 feet in areas where the alluvial aquifer is exposed are probably completed within lower Tertiary aquifers. Most permits within the interior Wind River Basin are within the "Potential Areas" identified in 2003; however, the prospective area covers a very large portion of the basin, so that it is unclear to what extent the designation had an effect on recent groundwater development patterns.

1.8.3 Paleozoic aquifer potential groundwater areas

The 2003 "Potential Areas of Future Ground Water Development" (BRS, Inc., 2003b) outlined areas with potential enhanced permeability in the Paleozoic aquifer around the perimeters of both the Wind River and Bighorn basins where folds and faults are expressed in outcrops of pre-Tertiary geologic units. Relative to the interior basins, a larger proportion of groundwater permits issued since 2000 in these areas (and adjacent areas outside the 2003 "Potential Areas") have been for greater depths ranging to more than 1000 feet across a wide range of yields. Many of the permits in the 2003 "Potential Areas" and adjacent areas have been located proximal to or generally along trend with mapped faults and anticlines. Many of these permits have surface locations within overlying Mesozoic aquifers and confining units. While many of the deeper wells probably targeted the Paleozoic aquifers, several are likely completed within Mesozoic units. It is apparent that a deeper understanding of the role of solution-enhanced permeability in Paleozoic carbonate aquifers **(Section 5.4)** has had a positive effect on groundwater development in the Paleozoic aquifers along the eastern flank of the Bighorn Basin.

Chapter 2
Background

Paul Taucher

The information on WBRB groundwater compiled for this study included regional and area-specific studies and Wyoming, Montana, and federal agency data.

2.1 Sources of data

Agencies that contributed data and information for this study are:	
U.S. Bureau of Land Management	BLM or USBLM
U.S. Environmental Protection Agency	EPA or USEPA
Montana Bureau of Mines and Geology	MBMG
Montana Geographic Information Clearinghouse	MGIC
Montana Geographic Information Clearinghouse	USGS
University of Wyoming Library System	–
University of Wyoming Water Resources Data System	WRDS
Wyoming Department of Environmental Quality	WDEQ
Wyoming Geographical Information Science Center	WyGISC
Wyoming Oil & Gas Conservation Commission	WOGCC
Wyoming Water Resources Research Institute	WRRI
Wyoming State Engineer's Office	WSEO
Wyoming State Geological Survey	WSGS
Wyoming Water Development Commission	WWDC
Wyoming Water Development Office	WWDO

2.2 Major previous regional-scale investigations

The major regional, basin-wide, county-wide, and reservation-wide hydrologic studies consulted for this memorandum came from the USGS, WRRI, WWDC, and WSGS:

For the Wind River and Bighorn basins and northwestern Wyoming:

- *U.S. Geological Survey Basin Hydrologic Investigations Atlases*

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

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

  1976 - Lowry, M.E., Lowham, H.W., and Lines, G.C., Water resources of the Big Horn Basin, northwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-512, scale 1:250,000.

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

1962 - Dana G. F., Groundwater Reconnaissance Study for the State of Wyoming, Part 5 – Wind River Basin, and Part 6 – Bighorn Basin; prepared for the Wyoming Natural Resource Board.

1981 - Libra, Robert, Doremus, Dale, and Goodwin, Craig, Volume II-A, Occurrence and characteristics of groundwater in the Bighorn Basin, Wyoming: Wyoming Water Resources Research Institute, University of Wyoming.

1981 - Richter, H.R., Jr., Volume IV-A, Occurrence and characteristics of ground water in the Wind River Basin, Wyoming: Wyoming Water Resources Research Institute, University of Wyoming.

- *Wyoming State Geological Survey publications on geothermal resources*

  1985 - Heasler, H.P., and Hinckley, B.S., Geothermal resources of the Bighorn Basin, Wyoming: Geological Survey of Wyoming Report of Investigations No. 29.

  1987 - Hinckley, B.S., and Heasler, H.P., Geothermal resources of the Wind River Basin, Wyoming: Geological Survey of Wyoming Report of Investigations No. 38.

For the Northern Great Plains and Rocky Mountain Coal Provinces, Wyoming Counties, and the Wind River Indian Reservation:

- *U.S. Geological Survey Water Recourses Investigations Open-File Reports, Open-File Reports, Water Resources Investigations Reports, and Water Supply Papers*

  1969 - McGreevy, L.J., Hodson, W.G., and Rucker, S.J. IV, Ground-water resources of the Wind River Indian Reservation, Wyoming: U.S. Geological Survey Water-Supply Paper 1576-I.

  1986 - Slagle, S. E., et al., Hydrology of Area 48, Northern Great Plains and Rocky Mountain Coal Provinces, Montana and Wyoming: U.S. Geological Survey Water Resources Investigations Open-file Report 84-1141.

  1987 - Peterson, D.A, Mora, K.L., et al., Hydrology of Area 51, Northern Great Plains and Rocky Mountain Coal Provinces, Montana and Wyoming: US Geological Survey Water Resources Investigations Open-File Report 84-734.

  1992 - Daddow, R.L., Ground-water and water-quality data through 1991 for selected wells and springs on the Wind River Indian Reservation, Wyoming: U.S. Geological Survey Open-File Report 92-455.

  1993 - Lowry, M.E., Smalley, M.L., et al., Hydrology of Park County, Wyoming, exclusive of Yellowstone

National Park: U.S. Geological Survey Water-Resources Investigations Report 93-4183.

1993 - Plafcan, Maria, Cassidy, E.W., and Smalley, M.L.,Water resources of Big Horn County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 93-4021.

1993 - Susong, D.D., Smalley, M.L., and Banta, E.R., Water resources of Washakie County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 91-4044.

1994 - Plafcan, Maria, and Ogle, K.M., Water resources of Hot Springs County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 93-4141.

1995 - Plafcan, Maria, Eddy-Miller, C.A., et al., Water resources of Fremont County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 95-4095.

1996 - Daddow, R.L., Water resources of the Wind River Indian Reservation, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 95-4223.

1996 - Whitehead, R.H., Ground water atlas of the United States, Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geologic Survey Hydrologic Investigations Atlas HA-730-I, 24p. ["Results of the U.S. Geological Survey Regional Aquifer System Analysis (RASA) Program were used as a major source of information for compilation of the Atlas."]

- *Wyoming Water Development Commission 2007 Wyoming Framework Water Plan and 2003 Available Groundwater Determination Technical Memorandum for the WBRB*

2003 - Wyoming Water Development Commission – Wind/Bighorn River Basin Water Plan Technical Memoranda and Executive Summary, by Lidstone and Associates, Inc.

2007 - Wyoming Water Development Commission – Wyoming Framework Water Plan,Volume I and Volume II, by WWC Engineering, Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., States West Water Resources Corporation, the Wyoming Water Development Office, the Wyoming State Engineer's Office, and the Wyoming Game & Fish Department.

2.3 This memorandum – 2011 WBRB Available Groundwater Determination

The study areas of previous regional hydrogeologic investigations of the WBRB were generally the structural Wind River and Bighorn basins (e.g., HA and WWRI studies) or counties or other specific areas of interest (USGS studies). This and the previous (2003) Available Groundwater Determination Technical Memoranda of the Wyoming Framework Water Plan are based on the surface drainage basins of the Wind/Bighorn River. Because of differences in stratigraphic nomenclature, the geology and hydrogeology of the Wind River and Bighorn basins are presented separately, and the Absaroka volcanics are presented as a third area where their lithology requires separate treatment.

Rather than discussing detailed stratigraphy, hydrogeologic characteristics, and groundwater quality of the aquifers in separate chapters, as was more or less the format in previous regional studies, this report combines these subjects in **Chapter 7** for the Wind River Basin **(Section 7.1)**, the Bighorn Basin **(Section 7.2)**, and the Absaroka Range and Yellowstone volcanic area **(Section 7.3)**, on the basis of hydrogeologic units and geologic units **(Appendix A)**. The hydrostratigraphy of each basin is also summarized in **Section 6.1**; on hydrostratigraphic nomenclature charts **(Plates II and III)**; on **Plate IV**, a surface hydrogeologic map and hydrostratigraphic chart; and on Plate V, which tabulates how geologic units are assigned to hydrogeologic units.

This memorandum gives particular attention to these topics:

- Effects of structure **(Sections 5.4 and 7.0)**; generation of hydrocarbons in the deep basin areas **(Section 5.5)**; and potential hydrothermal resources **(Section 4.7.3)**
- Aquifer vulnerability and potential sources of groundwater contamination **(Section 5.7)**
- Calculation of recharge volumes and comparisons with precipitation, total stored and potentially available groundwater volumes, and current and projected uses **(Section 6.2)**
- A detailed listing and summary of historic groundwater development studies by the WWDC in the WBRB **(Appendix B)**

2.4 Maps

The WSGS compiled maps for this report from a number of computer-based data sources. Several maps are based wholly or primarily on existing GIS databases and map layers compiled specifically for this study; use of GIS layers is tabulated in **Appendix C**. Some of these maps and layers were supplemented with information scanned or digitized from existing hard-copy maps into a format that could be merged with the GIS data for presentation. The accuracy of the maps presented in this study depends on the accuracy of the original data and on adjustments made to correlate separate data sets. Maps for this study were compiled in two formats: plate-scale (1:380,000; 1 inch = 6 miles) and figure-scale (to fit 8½ × 11-inch, 8½ × 14-inch, and 11 × 17-inch sheets). Because the sizes of the symbols used to locate specific features (wells, potential contaminant sources, etc.) on the maps greatly exceed the relative size of the features they represent, there are many areas with substantial overlap of symbols.

Online versions of the maps can be accessed via the Internet Map Server at:

http://waterplan.state.wy.us/plan/bighorn/bighorn-plan.html

Information on the various established GIS datasets, referred to as metadata (data about the data), is commonly provided along with the GIS data itself. Metadata includes structured and detailed descriptive information about the data resources used to develop GIS map layers. Metadata is used to augment and facilitate the understanding, use, and management of the data by identifying and defining its source, location, format, attributes, processing, limitations, disclaimers, etc. The metadata may include contact information. The metadata associated with the WBRB maps is online at:

http://waterplan.state.wy.us/plan/

Chapter 3

Description of the study area

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The WBRB drainage basin covers approximately 25 percent of the state in north-central and northwestern Wyoming, plus smaller areas of south-central Montana. **Figure 3-1** is an index map of the approximately 678 townships within the WBRB in Wyoming (625) and Montana (53). As determined from the GIS database developed for this study, the WBRB covers approximately 22,883 square miles (14.65 million acres) in Wyoming and 894 square miles (0.57 million acres) in Montana. The WBRB encompasses federal, state, and privately owned land in all or part of eight Wyoming counties:

- All of Big Horn, Park, and Hot Springs counties
- Approximately 95 percent of Washakie County
- Approximately 85 percent of Fremont County
- Approximately 10 percent of Teton County
- Small, relatively undeveloped parts of northwestern Natrona and western Johnson counties

Approximately 80 percent of Yellowstone National Park (in Park and Teton counties) is included in the drainage basin, as is the Wind River Indian Reservation (Fremont and Hot Springs counties). The northern WBRB (Bighorn Basin) includes small areas of Park, Sweet Grass, Carbon, and Big Horn Counties in south-central Montana.

The current population of the Wyoming WBRB is estimated to be 89,500 (MWH, 2010). The WBRB has a substantial rural population.

3.1 Physiography, landforms, topography, and surface drainage

In their surface-water report, MWH et al. (2010a, draft p. 13) describe the physiography of the WBRB as follows:

> "The basin is generally characterized by broad, rolling high plains with sparse vegetation surrounded by high mountains. The Wind River Range, Owl Creek Mountains, Absaroka Range and the Bighorn Basin are within the Middle Rocky Mountain major physiographic province, while the Wind River Basin is generally within the Wyoming major physiographic province, as defined by the WSGS. The Wind River Basin and the Bighorn Basin also form their own minor physiographic provinces within the major provinces."
>
> – MWH, 2010a

The WBRB is bounded by topographic or surface-water divides – and by the Wyoming state line in the northwestern corner of the state and along part of the northern border. The ten segments of the WBRB boundary enumerated below are shown in **Figure 3-2** and can be followed on those USGS 1: 500,000-scale maps of Wyoming and Montana that show streams and elevation. Clockwise from the Pryor Mountains in Montana, the boundary runs:

1. Northward then southeastward along a Pryor mountain ridgeline bordering drainage intoWyoming, to the Wyoming/Montana state line;
2. Thence eastward along the Wyoming/Montana state line and along a divide in the Bighorn Mountains;
3. Thence generally south-southeastward along the arcuate ridge of the Bighorn Mountains to T39N, R87W;
4. Thence generally south-southwestward along a divide on the Casper Arch from T39N, R87W to the northwestern tip of the Rattlesnake Hills, T34N, R89W;
5. Thence a short distance southeastward along the ridgeline of the Rattlesnake Hills into T33N, R88W;
6. Thence irregularly west-southwestward along the Beaver Divide (Beaver Rim) – an irregular drainage divide on the Casper arch north and west of the Granite Mountains – to T30N, R101W, where it meets the Continental Divide;
7. Thence following the Continental Divide northwestward along the ridge of the Wind River Range, past the western end of the Washakie Range, along the southwestern edge of the Absaroka Range, and along a divide on the Yellowstone Plateau to the Wyoming/Idaho/Montana state line intersection;
8. Thence along the state line northward then eastward around the northwestern corner of Wyoming;
9. Thence arcing into Montana along a divide bordering drainage into Wyoming in part of the Absaroka Range and continuing generally east-southeastward along a ridge line in the Beartooth Mountains to the Wyoming state line;
10. Thence eastward along the state line between the eastern edge of the Beartooth Mountains drainage and the western edge of the Pryor Mountain drainage into Wyoming, where the Bighorn structural basin opens north-northwestward into Montana.

In this memorandum, the WBRB comprises four, three, or two areas, according to context. In the context of geography and surface geology the WBRB comprises the four areas shown on **Figure 3-2**: the Wind River Basin, the Bighorn Basin, the Absaroka Range, and the Yellowstone Plateau. In the context of subsurface geology, Bighorn-basin pre-volcanic stratigraphy extends westward beneath the Absaroka Range volcanics, as shown on **Plate VI**, sections A-B' and B-B'. The sub-volcanic structure may be seen as a highly faulted and folded extension of the Bighorn basin on the basis of similar stratigraphy or as a separate basin, the Absaroka Basin of Sundell (1993), separated from the Bighorn Basin by the Cody Arch, on the basis of structure. Under either interpretation, the western and southwestern borders of the Absaroka Basin or extended Bighorn Basin is probably the Washakie Range.

In the context of hydrogeology, the Wind River Basin and Bighorn River Basin, having a far higher density of data than the Absaroka and Yellowstone areas, are the two areas of interest;

Explanation

- City or town
- Hydrologic divide between the Wind and Bighorn river basins
- Structural divide between the Wind and Bighorn basins
- WBRB boundary
- State boundary
- County boundary
- Township
- Wind River Indian Reservation boundary
- Yellowstone National Park boundary
- U.S. highway
- State highway

N

0 5 10 20 30 Miles

Data Sources:

Bureau of Land Management
Esri
Montana Department of Administration
Premier Data Services
Spatial Analysis Center
Spatial Data and Visualization Center
U.S. Census Bureau
U.S. Forest Service
Wyoming State Geological Survey

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Figure 3-1. Geographic index map, Wind/Bighorn River Basin.

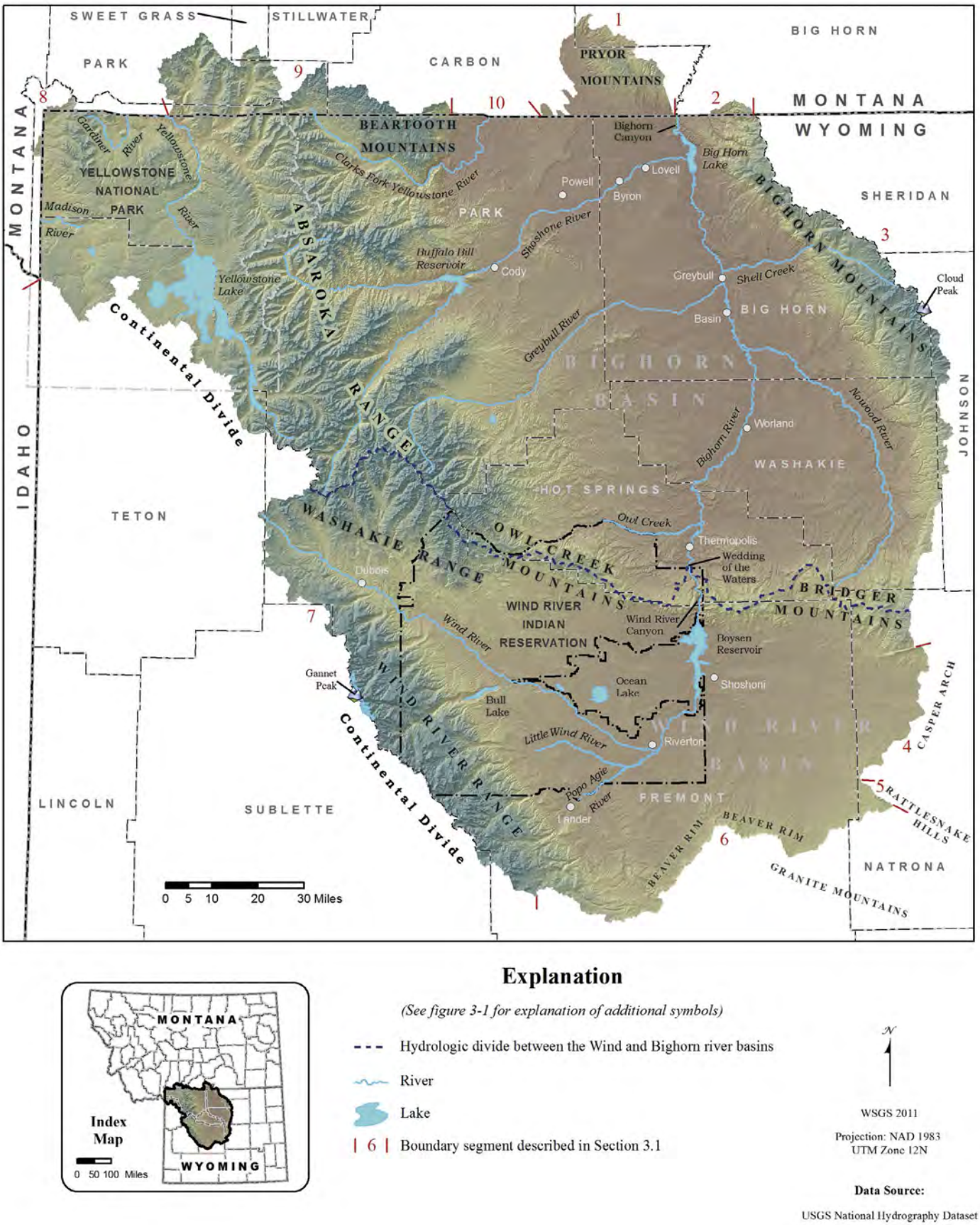

Figure 3-2. Major structural/physiographic features, drainages, and bodies of water, Wind/Bighorn River Basin (WBRB). Numbered segments (in red) of the WBRB boundary correspond to boundary description in Section 3.1.

and the Bighorn River Basin may include the eastern drainage of the Absarokas and sub-volcanic units beneath. In detailed hydrogeologic descriptions the Wind River Basin, Bighorn Basin, and Absaroka/Yellowstone areas are treated separately (Chapter 7).

The topography of the WBRB is defined by two intermontane basins surrounded and separated by mountain ranges, and the Yellowstone Plateau. Surface elevations within the WBRB drainage basin range from roughly 3,500 feet above sea level where the Bighorn River crosses the Wyoming/Montana state line in the Bighorn Basin to 13,804 feet at the summit of Gannett Peak in the Wind River Range. Within the basin interiors, elevations range from 4,000 to 6,000 feet. The Yellowstone Plateau in the northwestern corner of the WBRB is elevated relative to the basins, with elevations ranging from 7,731 feet at Yellowstone Lake to 12,244 feet at Trout Peak.

The WBRB drainage basin is a headwater of the Missouri River drainage system. Principal rivers include the Wind/Bighorn, Nowood, Greybull, Shoshone, Clark's Fork (Yellowstone), Yellowstone, Madison, and Gallatin and their tributaries **(Figure 3-2)**. The distal divides of these drainage systems define the limits of the WBRB study area. The Wind River structural basin – the basinal area bordered by uplifts – is drained by the Wind River and its tributaries. The Wind River leaves the Wind River Basin flowing northward through the Wind River Canyon, and becomes the Bighorn River at Wedding of the Waters just into the Bighorn Basin. Most of the Bighorn Basin and the eastern slope of the Absaroka Range is drained by the Bighorn River and its tributaries; a northern part of the eastern slope of the Absarokas and a contiguous southern part of the Beartooth Mountains are drained by the Clarks Fork Yellowstone River. The Bighorn River and Clarks Fork leave the Bighorn Basin flowing northward across the Wyoming/Montana state line. Much of the Yellowstone Plateau within the WBRB and the western slope of the Absarokas is drained by the Yellowstone River; small areas in the northwestern corner of the state are drained by the Madison River and Gardiner River. The Yellowstone and Gardiner Rivers leave the state flowing northward – the Madison flowing westward – across the Wyoming/Montana state line.

3.2 Climate, precipitation, and vegetation

The climate within the WBRB is primarily a function of altitude – to a lesser degree latitude and topography – and ranges from semi-arid continental within the basin interiors to humid-alpine in the bordering mountain ranges. The mountain ranges surrounding the basins tend to catch much of the atmospheric moisture flow through precipitation caused by orographic uplift, substantially decreasing precipitation in the basin interiors. Temperature varies by season from well below zero degrees Fahrenheit in the winter to more than 100 degrees in the summer. Most precipitation within the WBRB occurs during winter as snowfall and during spring and summer as thunderstorms (Libra et al., 1981). Average annual precipitation ranges from 6 to 10 inches in the basin interiors, 11 to 20 inches along the elevated foothills of the basins, 21 to 45 inches in the mountain ranges, and up to 70 inches along the mountain peaks above approximately 10,000 feet elevation **(Figure 3-3)**. Average annual precipitation within Yellowstone National Park ranges from 13 to 70 inches (**Figure 3-3**; Cox, 1976). For an updated map of mean annual precipitation within the WBRB (1971-2008) see MWH et al., 2010, **Figure 6**.

Vegetation in the WBRB is influenced by elevation, soil, exposure, and precipitation. In the lowland basin areas, mixed-grassland and sagebrush steppe vegetation dominates, with grasses, sagebrush, saltbush, greasewood, and desert shrub; and with cottonwood and Russian olive trees along drainages. Some of the lowland areas, especially along perennial streams, have been converted to cropland. Higher-altitude desert vegetation along the uplifts and foothills adjacent to the surrounding mountains includes a greater abundance of grasses, sagebrush, saltbush, greasewood, and desert shrub, along with woodland species that include cottonwood, willow, boxelder, juniper, and limber pine. Alpine forest and alpine tundra are characteristic of the higher mountain regions; vegetation includes a variety of grasses, sagebrush, lodgepole pine, ponderosa pine, spruce, fir, and aspen. Above timberline (approximately 10,000 feet), tundra supports alpine grasses (Peterson, Mora, et al., 1987).

3.3 Setting – Wind River Basin

This section describes the setting of the Wind River Basin, as derived primarily from Richter, 1981 and Libra et al., 1981.

3.3.1 Physiography and topography

The Wind River Basin as defined for this memorandum **(Figure 3-2)** covers an area of approximately 7,900 square miles; it is approximately 150 miles east-west and approximately 100 miles north-south. The structural basin is bordered on the southwest by the Wind River Range, on the northwest by the Absaroka Range and Washakie Range, on the north by the Owl Creek and Bridger Mountains, on the east by the Casper Arch and Rattlesnake Hills, and on the southeast by the Beaver Divide (Beaver Rim) section of the Casper Arch. Drainage from the basin is to the north where the Wind River transects the Owl Creek Mountains **(Figure 3-2)**.

The topography within the interior of the basin is characterized by gently rolling plains broken by broad river valleys, narrow terraces, and badlands. Elevations within the basin interior range from 5,400 to 6,000 feet above sea level. The lowest elevation within the Wind River Basin is 4,336 feet, at the base of Boysen Dam where the Wind River enters Wind River Canyon. The bounding mountain ranges rise steeply on the

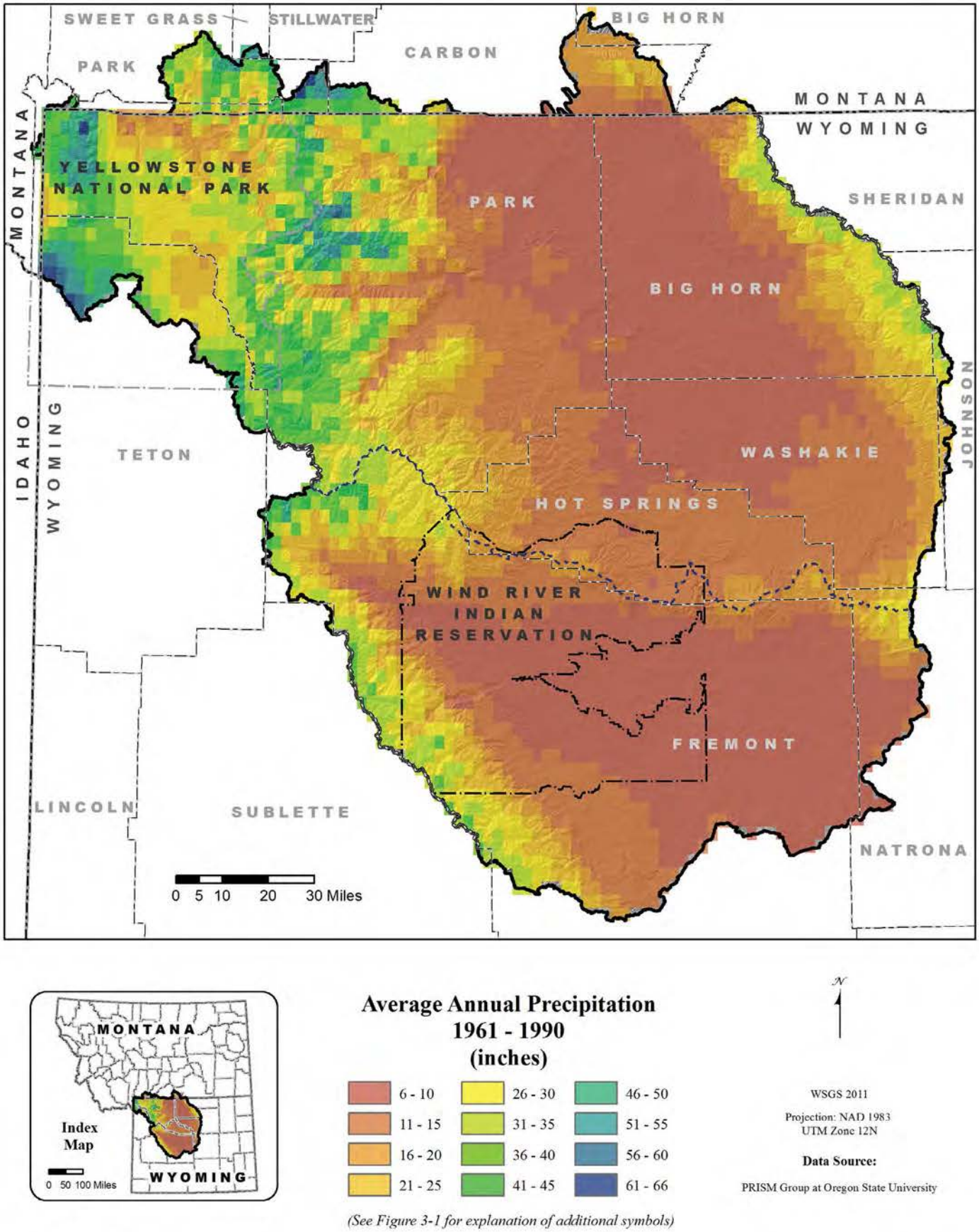

Figure 3-3. Average annual precipitation (1961 – 1990), Wind/Bighorn River Basin**.**

western and northwestern sides of the basin and more gradually on the eastern and southern sides. Elevations in the mountains commonly exceed 10,000 feet, reaching a maximum of 13,804 feet at Gannet Peak in the Wind River Range. Total topographic relief in the Wind River Basin is approximately 9,500 feet.

3.3.2 Surface drainage

Major drainages in the Wind River Basin headwater in the Wind River Range. Most flow in perennial streams is from snowmelt in the mountains. Rejected recharge from Mesozoic through Precambrian aquifers in the Wind River Range and irrigation return flows from Quaternary and Tertiary aquifers add to perennial flows. Ephemeral streams in the central basin flow only in response to thunderstorms and do not contribute significantly to overall stream flow. The Wind River, which drains the Wind River Basin, flows southeastward from the westernmost border of the basin to near Riverton, where it swings northwestward and then northward to drain the basin through Wind River Canyon. The Wind River continues northward in the Bighorn Basin to Wedding of the Waters, where it becomes the Bighorn River. Major streams and their tributaries within the Wind River Basin are listed in **Table 3-1**; several are shown in **Figure 3-2**, and all are shown on **Plate I and IV**.

3.3.3 Population distribution, land use, and land ownership

Every large community within the Wind River Basin is located within a few miles of a major stream or river. Riverton, Dubois, and Shoshoni were developed along the Wind River, and Lander was developed near the Popo Agie River. Only a few settlements have been located where there is no nearby supply of surface water; these settlements generally are associated with mineral development.

Land use in the Wind River basin is controlled primarily by the distribution of surface waters, precipitation, and the location of mineral resources. In the high mountain areas, above timberline, the alpine lands are generally used only for recreational purposes. At lower elevations, thickly forested areas are utilized for recreation and limited logging. Grazing is the dominant use on grasslands along the mountain fronts and riparian areas. Approximately 55 percent of the land within the basin is utilized for agriculture. Approximately 6 percent of the basin is irrigated cropland, and 85 percent of the cropland is on the Wind River Indian Reservation. Croplands are located primarily along the major streams where irrigation with surface water is possible. Most of the basin lowlands are covered sparsely with sagebrush and are used for grazing. The locations of active and historic mineral development properties are shown on **Figures 5-3, 5-7, 5-8, and 5-9** (and see Section 5.7.2 on potential groundwater contaminant sources).

Table 3-1. Wind River Basin surface drainage divisions by tributary rank and downstream order.

Wind River
Du Noir Creek[1]
Horse Creek[1]
Wiggins Fork[1]
Dinwoody Creek
Crow Creek[1]
Bull Lake Creek
Little Wind River
Sage Creek
North Fork
South Fork
Popo Agie River
North Popo Agie River
Little Popo Agie River
Beaver Creek
Muskrat Creek[2]
Fivemile Creek[3]
Poison Creek[2]
Badwater Creek[2]
Muddy Creek[4]

[1]Flows south from the Absarokas

[2]Flows west

[3]Flows southeast from the Owl Creeks

[4]Flows east, fed from the Owl Creeks

Table 3-2. Bighorn Basin surface drainage divisions by tributary rank and downstream order.

Yellowstone River		
Clarks Fork Yellowstone River		
	Sunlight Creek	
	Pat O'Hara Creek	
	Big Sand Coulee	
Bighorn River		
	Owl Creek	
	Kirby Creek	
	Cottonwood Creek	
	Gooseberry Creek	
	Nowater Creek	
	Fifteen Mile Creek	
	Nowood River	
		Tensleep Creek
		Paint Rock Creek
	Greybull River	
		Wood River
	Dry Creek	
	Shell Creek	
	Shoshone River	
		North Fork
		South Fork

Industrial, residential, and recreational areas occupy nearly all nonagricultural land.

Approximately **47** percent of the land area of the Wind River Basin is federally owned; it is controlled by the U.S. Bureau of Land Management within the basin lowlands and by the U.S. Forest Service in the forested/mountainous areas. The Wind River Indian Reservation occupies **34** percent – 68 percent of the reservation area is owned and managed by the Eastern Shoshone and Arapaho Tribes, and 32 percent is under jurisdiction of the U.S. Bureau of Reclamation. Approximately **15** percent of the land in the basin is privately owned – it is concentrated along rivers and streams; **4** percent is owned by the State of Wyoming; and **less than 1** percent is owned by other entities.

3.4 Setting – Bighorn Basin

This section describes the setting of the Bighorn Basin, as derived primarily from Libra et al., 1981.

3.4.1 Physiography and topography

The Bighorn Basin as defined for this memorandum **(Figure 3-2)** covers an area of approximately 12,500 square miles, measuring approximately 140 miles east-west and approximately 100 miles north-south to the Montana state line – and continues northward about 22 miles into Montana. The basin is bordered on the northeast by the Pryor Mountains, on the east by the Bighorn Mountains, on the south by the Owl Creek and Bridger mountains, and on the northwest by the Beartooth Mountains. To the west, the structural basin is covered by the volcanic Absaroka Range and extends westward onto the Yellowstone Plateau. The basin is open northward into Montana.

The topography of the basin interior is characterized by rolling plains broken by broad river valleys, narrow terraces, and badlands. Elevations in the plains range from 4,000 to 5,600 feet above sea level. The lowest elevation within the Bighorn Basin is approximately 3,500 feet, where the Bighorn River crosses the Wyoming/Montana state line. The bounding mountain ranges rise steeply on the eastern, western, and northwestern sides of the basin and more gradually on the southern side. Elevations in the mountains commonly exceed 10,000 feet, reaching a maximum of 13,175 feet at Cloud Peak in the Bighorn Mountains. Total topographic relief in the Bighorn Basin is approximately 9,700 feet.

3.4.2 Surface drainage

Most flow in perennial streams is from snowmelt in the mountains. Rejected recharge from Mesozoic through Precambrian aquifers in the surrounding mountains and irrigation return flows from Quaternary and Tertiary aquifers add to perennial flows. Ephemeral streams in the central basin flow only in response to thunderstorms; they do not contribute significantly to overall stream flow. The Wind/Bighorn River is the primary drainage for the WBRB drainage basin. The river cuts the Wind River Canyon through the Owl Creek Mountains, which separates the two structural basins. The name changes from Wind River to Bighorn River a few miles south of Thermopolis at the mouth of Wind River Canyon, a location called "Wedding of the Waters." The Bighorn River, which drains most of the structural BHB, flows northward from Wedding of the Waters and into Montana. The Clarks Fork Yellowstone River drains a small north-central area of the basin, and the Yellowstone River drains much of the Yellowstone Plateau; both rivers flow northward into Montana. Major streams and tributaries in the Bighorn Basin are listed in **Table 3.2**, and some are shown in **Figure 3-2**.

3.4.3 Population distribution, land use, and land ownership

Every large community within the Bighorn basin is located within a few miles of a major stream or river. Worland, Thermopolis, Basin, and Greybull were developed along the Bighorn River, and Cody, Powell, and Lovell were developed near the Shoshone River. Only a few settlements have been located where there is no nearby supply of surface water; these settlements generally are associated with mineral development.

Land use in the Bighorn Basin is controlled primarily by the distribution of surface waters, precipitation, and the location of mineral resources. In the high mountain areas, above timberline, the alpine lands are generally used only for recreation. At lower elevations, thickly forested areas are utilized for recreation and limited logging. Grazing is the dominant use on grasslands along the mountain fronts and riparian areas. Croplands are located primarily along the major streams where irrigation with surface water is possible. Most of the basin lowlands are covered sparsely with sagebrush and are used moderately for grazing. The locations of active and historic mineral development properties are shown on **Figures 5-3, 5-7, 5-8, and 5-9** (and see Section 5.7.2 on potential groundwater contaminant sources). Industrial, residential, and recreational areas occupy nearly all the nonagricultural land.

Approximately three-quarters (75.2 percent) of the of the land in the Bighorn basin is federally owned; it is controlled by the U.S. Bureau of Land Management (33 percent), the U.S. Forest Service (22.8 percent), the National Park Service (16.6 percent), and the Bureau of Indian Affairs, Bureau of Reclamation, and Department of Defense (together ~ 2.8 percent). Approximately 4.3 percent of the land in the basin is owned by the State of Wyoming, and approximately 20 percent is privately owned. The privately owned property is concentrated along rivers and streams.

Chapter 4

Geologic Setting

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The geologic framework of WBRB groundwater regime is the assemblage of geolgic units and structural elements that define the several groundwater basins. Geologic units are derived from mapped lithostratigraphic units: the formations, members, tongues, and so forth established in formal and informal geologic usage.

Plate I is a surface geology map of the WBRB. Detailed descriptions of the WBRB geologic units are provided in Appendix A. The cross sections on **Plate VI** show typical subsurface structure in the WBRB. Isopach maps on **Plates VII and VIII** show the variation in thickness of selected WBRB aquifers and confining units.

Plate IV maps the outcrop areas of hydrogeologic units in the WBRB on the basis of correlation of hydrogeologic and lithostratigraphic units defined on **Plates II and III** and discussed in **Section 6.1. Plate V** defines how WBRB geologic units were assigned to hydrogeologic units for mapping on **Plate IV**.

4.1General/historical geology

Simple to complex stratigraphic, structural, and volcanic elements are present within the WBRB. The configuration of these elements and relationships among them influence the availability of groundwater. The geologic history relevant to groundwater resources of the WBRB, as described by Libra et al. (1981), Richter (1981), and Snoke (1993), starts with the nonconformable deposition of transgressive marine sediments onto Precambrian basement rocks during Middle Cambrian time. From that time forward, the stratigraphic, structural, and volcanic elements that record the geologic history of the WBRB are as follows:

1. Paleozoic strata in the WBRB were deposited in marine and nonmarine transgressive/regressive environments. Marine limestones and dolomites are the dominant lithologies of the Paleozoic sequence, with less extensive sandstones and shales that represent beach and near-shore environments. Deposition in the Paleozoic Era was broken by long periods of erosion, as indicated in the geologic record by several regional unconformities.

2. The early Mesozoic Era was a time of shallow seas with deposition of interbedded layers (in decreasing abundance) of sandstone, siltstone, shale, carbonates, and evaporates. An emergent transition to a terrestrial environment during the Late Triassic and Early Jurassic Epochs resulted in the deposition of marginal marine, eolian, fluvial, and paludal sandstones and shales.

3. During the Early Cretaceous Epoch a thick section of interbedded shale, sandstone, siltstone, and claystone was deposited under terrestrial, shallow marine, and deltaic conditions. Late Cretaceous transgressions and regressions resulted in a thick sequence of interbedded sandstone, siltstone, claystone, and shale deposited in marine, marginal marine, coastal plane, and deltaic environments. Crustal deformation associated with the Laramide Orogeny began in the Late Cretaceous; the Lance Formation recorded the final, eastward retreat of the Cretaceous seas followed by the deposition in terrestrial environments that would prevail throughout the Tertiary Period.

4. Laramide compressional deformation continued through the early Eocene with large-scale reverse and thrust faults forming the basement-cored mountain ranges and uplifts that surrounded and separated the concurrently subsiding Wind River and Bighorn structural basins. The uplifted areas were the source of several thousand feet of Tertiary sediments composed of Mesozoic, Paleozoic and Precambrian rocks that were eroded from the uplifts and filled the basins to the extent that all but the highest areas of the surrounding uplifts were buried. These strata are composed of conglomerates, sandstones, and claystones deposited primarily in fluvial, alluvial fan, and lacustrine environments. During the middle Eocene a pile of rhyolitic and basaltic volcanic rocks several thousand feet thick (Absaroka Supergroup and intrusive rocks) were emplaced along the western side of the Bighorn Basin and in the Yellowstone area.

5. Late Tertiary normal faulting concurrent with modest extension occurred throughout Wyoming. Uplift during the past 5 million years over a broad area that encompasses the WBRB resulted in the erosion and removal of an enormous volume of Tertiary strata, exhuming the Laramide framework and sculpting the present physiography of the WBRB. The massive pile of volcanic material that forms the Yellowstone Plateau is composed of rhyolitic and basaltic rocks (Yellowstone Group) associated with the active Yellowstone mantle hotspot and caldera, erupted during the past 2.2 million years.

6. The youngest geologic units in the basin are unconsolidated Pliocene and Quaternary terrace deposits and Quaternary alluvial deposits of various thickness. These deposits, some as much as several hundred feet thick, are composed of conglomerate, gravel, sand, and finer-grained clastic material. The age and occurrence of these deposits have been correlated with recent glacial and interglacial periods by Mackin (1937).

4.2 Structural geology

The Wind River and Bighorn basins are large asymmetric intermontane structural basins formed during the Laramide Orogeny (Late Cretaceous-Eocene) that contain up to 18,000 and 33,000 feet, respectively, of Cenozoic, Mesozoic, and Paleozoic sediments deposited on Precambrian crystalline basement rocks (Libra et al., 1981; Richter, 1981). With the exception of the western Bighorn Basin that is largely covered by the Absaroka volcanics, the structural basins are bordered by compressional uplifts cored by Precambrian granite and mantled by moderately to steeply dipping sedimentary formations (Libra et al., 1981). Laramide structural trends are thought to extend westward below the massive volcanic pile of the Absaroka/Yellowstone area. Paleozoic and Mesozoic formations exposed along the flanks of the mountain ranges surrounding the WBRB were folded, faulted, and eroded from the highest areas of the uplifts during the Laramide Orogeny; they now dip basinward at angles ranging from approximately 10 degrees to vertical, and some are overturned. Strata of Paleocene through early Eocene age are also deformed around the perimeters of both structural basins but are mostly flat-lying in the interior basin areas. Numerous anticlinal structures with associated faults and fractures that formed during the Laramide Orogeny crop out along the margins of both basins. Section 5.4 discusses the substantial influence that structures, primarily those located around the basin perimeters, exert on the groundwater resources.

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

The major Laramide structural elements of the WBRB **(Figure 3-2)** comprise:

- The folded and faulted Precambrian basement
- The deeply buried downwarped areas of the Wind River and Bighorn basins
- The mountain ranges and uplifts that surround and separate the basins:
    - the Pryor Mountains
    - the Bighorn Mountains
    - the Washakie Range, Owl Creek Mountains, and Bridger Mountains
    - the Casper Arch and Beaver Divide
    - the Wind River Range
    - the Beartooth Mountains

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

4.3 Stratigraphy

Geologic units within the WBRB vary widely in lithology and distribution, and range in age from Precambrian crystalline rocks to recent alluvial and terrace deposits. The Wind River Basin contains a maximum of approximately 18,000 feet, the Bighorn Basin a maximum of approximately 33,000 feet, of Cenozoic through Paleozoic sedimentary strata. The explanation on **Plate I** identifies the geologic units present in the basin; the individual geologic units are described in **Appendix A**. The distribution of geologic units reflects several periods of deposition, uplift, erosion, volcanism, and reworking/re-deposition of older units as younger strata. The erosion of rocks exposed in upland areas and re-deposition in the basins is an ongoing process. Accordingly, the stratigraphic sections preserved in interior basin areas are most complete, and stratigraphic sections are less complete to non-existent at higher elevations in the surrounding mountain ranges. In some places Tertiary and Quaternary deposits directly overly Precambrian basement rocks.

4.4 Wind River Basin and surrounding mountain ranges (Richter, 1981)

The Wind River Basin contains a maximum 18,000 feet of Cenozoic through Paleozoic sedimentary strata. The Wind River structural basin is bounded on the north by the Owl Creek and Bridger Mountains, on the east by the Casper Arch, on the southeast by the Beaver Divide, on the southwest by the Wind River Range, and on the northwest by the Absaroka Range and Washakie Range **(Figure 3-2)**.

The structure contour map of the Precambrian basement surface **(Plate I, inset)** shows that the axis (deepest area) of the structural basin is located along and parallel to the abrupt northern limit of the basin, 3 to 15 miles south of the Owl Creek and Bridger Mountains. Because the basement has been eroded in the mountains, maximum structural relief between the deepest area of the basin and the highest area of the uplifts exceeds the 38,000 feet defined by the difference between elevations in the deepest part of the structural basin at approximately 24,000 feet below sea level and at Gannet Peak at nearly 14,000 feet above sea level in the Wind River Range (Blackstone, 1993).

4.5 Bighorn Basin and surrounding mountain ranges (Libra et al., 1981)

The Bighorn Basin contains a maximum of 33,000 feet of Cenozoic through Paleozoic sediments. The Wyoming Bighorn Basin is open to the north along the Wyoming/Montana border and is bounded on the northeast by the Pryor Mountains, on the east by the Bighorn Mountains, on the south by the Owl Creek and Bridger Mountains, on the west by the Absaroka volcanics, and on the northwest by the Beartooth Mountains. It is likely that Laramide structures are buried beneath the Absaroka/Yellowstone volcanic pile (Thom, 1952).

The structure contour map **(Plate I)** of the Precambrian basement surface shows that the synclinal axis of the Bighorn Basin is located along the west side of the basin and trends generally northwest-southeast, parallel to the overall structural grain of the area. Because the basement has been eroded in the mountains, maximum structural relief between the deepest area of the basin and the highest area of the uplifts exceeds the 38,000 feet defined by the difference between elevations in the deepest part of the structural basin, approximately 24,000 feet below sea level, and on Cloud Peak nearly 14,000 feet above sea level in the Bighorn Mountains (Blackstone, 1993).

4.6 Owl Creek Mountains, Bridger Mountains, and Washakie Range

The Owl Creek and Bridger mountains compose one of the three Laramide uplifts in Wyoming that trend east-west. The uplift is a continuous structural and drainage divide between the Wind River and Bighorn basins, that runs between the south end of the Absaroka Range and south end of the Bighorn Mountains. The Owl Creek and Bridger mountains were uplifted along imbricate, south-verging thrust faults. Sedimentary strata ranging in age from Cambrian to Tertiary are exposed in the range. Precambrian rocks are exposed in the Wind River Canyon and along the ridge of the Bridger Mountains east of the canyon. Minor Quaternary deposits flank the uplift north and south. The highest areas of the range are substantially lower than the highest areas of the Absaroka or Bighorn ranges.

The Washakie Range, located at the west end of the Owl Creek Mountains between the northernmost extent of the Wind River Range and southern edge of the Absaroka Range in the northwestern Wind River Basin (Love 1937), is defined by a west-northwest-trending series of en echelon, faulted folds where geologic units ranging from Precambrian to Tertiary are exposed. The north side of the Washakie Range structural trend is buried beneath the Absaroka Range volcanics.

4.7 Volcanic and geothermal areas

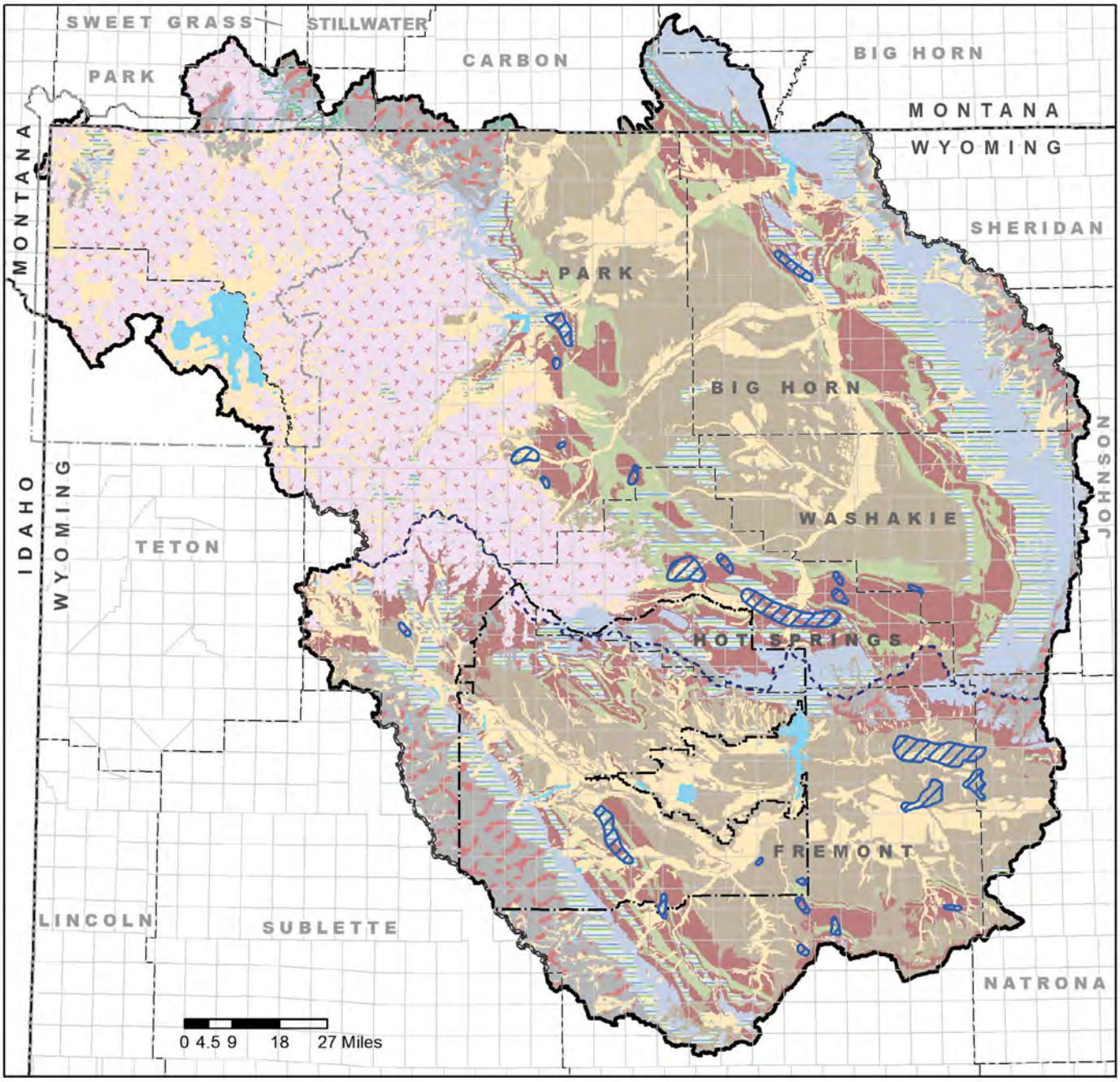
Plates I and IV show the Absaroka Range and the Yellowstone Plateau, major volcanic elements within the WBRB. The Yellowstone area is characterized by major high- and low-temperature geothermal features. Although lacking associated volcanic material, the Thermopolis area, on the south end of the Bighorn Basin (north flank of the Owl Creek Mountains), and thermal springs near Dubois in the Wind River Basin are also notable (low-temperature) hydrothermal areas within the WBRB.

4.7.1 Absaroka Range and Volcanic Province (Sundell, 1993)

The depositional and erosional origin of the Absaroka Range is completely different from that of the typical Laramide uplifts that bound the WBRB. The pile of middle to late Eocene volcanic material that composes the Absaroka Range and associated Absaroka Volcanic Province was deposited on top of Cenozoic, Mesozoic, and Paleozoic sedimentary strata in a shallow foreland topographic and structural basin immediately west of the Bighorn Basin **(Plate I)**. The proposed source of the volcanic material is a belt of large andesitic stratovolcanoes. The Absaroka deposits comprise primary volcanic material (minor intrusive igneous rocks, lava flows, flow breccias, pyroclastic breccias, and tuffs) and re-worked volcaniclastic material (conglomerate, sandstone, siltstone, claystone, and breccia) with a combined maximum thickness of more than 6,000 feet.

The Absaroka Volcanic Province is a remnant of a much more extensive accumulation of volcanic material that formerly covered a much larger area of northwestern Wyoming. The Absarokas represent the largest Eocene volcanic field in the Northern Rocky Mountains. Reworking of the volcanic material included gravitational slide and flow mass-movements that produced three of the largest landslides on Earth. In addition, the Absaroka volcanic rocks were deformed by Laramide folding and faulting (earliest deposits), igneous intrusion, and post-volcanic extension and compaction.

Although high precipitation and high estimated recharge rates (Section 6.2.2) indicate that the Absaroka volcanic area could contain substantial groundwater resources, the complex to chaotic stratigraphy, elevation, extremely rugged topography, volcanic terrains, harsh climate, lack of roads, and other impediments to access (e.g., National Park or Wilderness designations) severely restrict exploitation of such resources. The deeply eroded terrain and stratigraphy within the Absaroka Province greatly restricts aquifer continuity and storage within the volcanic aquifer system. Most groundwater within the volcanics probably exists in perched and isolated accumulations. Natural discharge into streams that headwater in the mountains probably contributes substantial surface flow.



Explanation

(See Figure 3-1 for explanation of additional symbols)

Area of anomalous thermal gradients

Hydrogeologic Units

- Ice
- Water
- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

N

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Heasler and Hinckley (1985)
Hinckley and Heasler (1987)

Figure 4-1. Potential hydrothermal resource areas, Wind/Bighorn River Basin, Wyoming.

4.7.2 Yellowstone Plateau (Keefer, 1971)

The Absaroka volcanic rocks are overlain by Late Pliocene and Quaternary volcanic deposits of the Yellowstone Plateau along the eastern margin of Yellowstone Park **(Plate I)**. The geology and hydrology of the Yellowstone volcanic area are dominated by the Yellowstone hotspot, associated large-scale historic volcanic events, including caldera eruptions, and ongoing widespread geothermal activity (Cox, 1976; Libra et al., 1981). The Yellowstone Plateau is separated from the rest of the WBRB by the Absaroka Range. Because most of the Yellowstone area is a National Park, the groundwater and hydrothermal resources of the area are not available for use outside the Park and are not considered relevant to this WBRB Available Groundwater Determination.

4.7.3 Geothermal resources (Heasler and Hinkley, 1985; Hinkley and Heasler, 1987)

The geothermal resources of the WBRB (exclusive of the Yellowstone Plateau) are of the low-temperature hydrothermal type, occurring where groundwater at anomalously elevated temperature (relative to the average geothermal gradient) is at a depth where it can be put to beneficial use. In this sense the hydrothermal resources are similar to direct-use groundwater resources. Hydrothermal resources of the WBRB are primarily suited to local, small-scale projects that utilize low-temperature waters for space-heating, de-icing, agriculture (e.g., greenhouses), aquaculture, recreational/ therapeutic applications (e.g., Thermopolis hot springs), or low-temperature processing.

Generally, groundwater is heated as it flows downdip into a structural basin in accord with the local geothermal gradient resulting from heat flow from deep in the earth toward the land surface. WBRB hydrothermal resources occur primarily where the heated groundwater rises to shallower depth under artesian hydraulic pressures at velocities that preclude dissipation of the heat acquired at depth. This requires vigorous upward flow through permeable up-folded strata or up faults, fracture systems, or wells. In general, the conditions that control hydrothermal resources occur only within the more productive Mesozoic and Paleozoic aquifers in the WBRB. The locations of known and potential areas of hydrothermal resource development (exclusive of Yellowstone Park) are shown on **Figure 4-1**.

4.8 Mineral resources

The development (production, processing, and transportation) of mineral resources generally requires the use and proper disposal or surface discharge of groundwater. The development of mineral resources may create avenues for groundwater contamination. In addition, the mineral content of aquifers, especially where specific minerals are concentrated (e.g., uranium, arsenic, hydrocarbons) can negatively affect groundwater quality. **Figures 5-3, 5-7, 5-8, and 5-9** show the distribution of oil-and-gas operations and other active and historic mineral development locations within the WBRB (Section 5.7.2).

Significant quantities of oil and gas have been developed in the WBRB. Substantial uranium and minor coal and feldspar have been commercially developed in the Wind River Basin. Coal, bentonite, and gypsum have been commercially developed in the Bighorn Basin. Industrial minerals including sand, gravel, clay, limestone, dolomite, shale, zeolites, talc, sulfur, and pumice have been produced within the WBRB, and some still are. The WSGS has mapped potential metal ore development areas for gold, silver, titanium, copper, and rare earths, and private companies have explored for metals; however, there are no current metal mining operations in the WBRB.

Most oil and gas has been developed in the Bighorn Basin in Mesozoic and older geologic units from stratigraphic traps and structural anticlines, and in the Wind River Basin from stratigraphic and structural traps in Tertiary and Cretaceous geologic units. Minor coalbed natural gas (CBNG) is currently being developed in the northern Bighorn Basin and the southern Wind River Basin, and there is good potential for additional CBNG development in both basins. Substantial uranium has been produced from the Wind River Formation in the southeastern Wind River Basin. Uranium is not currently being produced; however, substantial deposits remain that could be developed in the future. Bentonite is produced from Cretaceous strata in the northern Bighorn Basin. Gypsum is quarried from the Gypsum Spring Formation in the northwestern Bighorn Basin. Abundant coal is present in the WBRB in lower Tertiary and Cretaceous strata, with superior resources and minor production in the Grass Creek area of the Bighorn Basin. However, Grass Creek coal is not competitive with coal produced in other Wyoming basins and other states except for local use, so production is not expected to grow.

Chapter 5

Technical Concepts: Hydrogeology and Groundwater Quality

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This chapter presents technical concepts and terminology used in this study. U.S. Geological Survey Water Supply Paper 2220 (Heath, 1983) provides a general discussion of groundwater resources. *Hydrogeology* is the area of geology that deals with the distribution and movement of groundwater through the bedrock and unconsolidated material (including soil) of the Earth's crust. 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 interdisciplinary, requiring knowledge of geology (the plumbing and storage) as well as with physical, chemical, and biological interactions among water, rocks, unconsolidated materials, and the surface environment. These aspects of groundwater resources are interconnected in real-world groundwater systems.

Hydrogeology deals generally with groundwater that is accessible and can be directly used for the benefit of society. The shallowest groundwater resources (generally water-table aquifers and shallow confined aquifers) and their interactions with surface water are of interest in the fields of soil science, agriculture, and civil engineering. The hydrogeology of groundwater in deeper formations, which is not directly useful as a commodity due to inaccessibility and poor quality, is of interest primarily to mineral and petroleum resource geologists, geophysicists, and petroleum engineers. Suitability for beneficial use depends on water quality. In this study, groundwater quality is described in terms of suitability for domestic, irrigation, and livestock use on the basis of U.S. Environmental Protection Agency (USEPA) and Wyoming Department of Environmental Quality (WDEQ) water-quality standards (Section 5.6.1; Chapter 7).

5.1 Definitions and concepts

The movement of groundwater through, and its interaction with, permeable earth materials can be complex: highly variable geologic, chemical, and hydraulic properties control flow, chemical composition, and availability. Groundwater is a generally slow-moving, viscous fluid that flows through interconnected voids from areas of higher to areas of lower hydraulic pressure. The voids range in size from microscopic to cavernous. The chemistry of groundwater is affected by the mineral composition of the bedrock and unconsolidated materials through which it flows and by residence time.

5.1.1 Definitions

The following terms and concepts are used frequently in this study. Definitions of less frequently used terms and concepts are provided in the Glossary, **Section 5.8**.

- *Geologic unit* – a scale-sensitive map unit depicting a lithostratigraphic unit or group of lithostratigraphic units. With the development of GIS technology, the Wyoming geologic units have been compiled into a database that can be manipulated electronically to present the geologic units grouped according to specified criteria – such as the hydrologic characteristics described in this memorandum. A discussion of geologic units is provided in **Section 5.2**.

- *Lithostratigraphic unit* – a rock unit defined on the basis of lithologic consitstency, depositional continuity, and stratigraphic association. These are the formations, members, lenses, tongues, beds, flows, and other stratigraphic units and groups of rocks that have been correlated, named, and mapped by geologists. For additional discussion of lithostratigraphic units, see **Section 5.2**.

- *Hydrogeologic unit* – one or several contiguous geologic units or parts of geologic units characterized by hydrologic characteristics; i.e., classified as an aquifer or a confining unit.

- *Aquifer* – a hydrogeologic unit composed of a geologic unit, group of geologic units, or part of a geologic unit that contains sufficient water-saturated and permeable material to yield sufficient quantities of water to wells and springs (modified from Lohman et al., 1972), with "sufficient" generally defined in terms of use. An aquifer both stores water and functions as a conduit for groundwater flow. Aquifers are not defined on the basis of geologic unit boundaries, but on the hydraulic and recharge/discharge characteristics of the geologic units that compose them.

- *Aquifer system* – a heterogeneous body of saturated, interbedded geologic units with variable permeabilities that functions regionally as a major integrated water-bearing hydrogeologic unit; it comprises two or more smaller aquifers separated, at least locally, by strata with low permeability that impede groundwater movement between the component aquifers but do not preclude the regional hydraulic continuity of the system (modified from Poland et al., 1972). Aquifers and aquifer systems are generally anisotropic because of interbedded low-permeability strata (e.g., shale, claystone, mudstone, bentonite). Aquifer systems generally:
    - are regionally extensive
    - have common recharge and discharge areas and mechanisms
    - have similar hydraulic properties
    - have similar water-quality characteristics
    - are sealed from younger and older aquifers/aquifer systems by thick and laterally extensive confining units

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

- *Confined aquifer* – an aquifer overlain and underlain by confining units that limit groundwater flow into and out of the aquifer. Confined aquifers are completely saturated and under confining (*artesian*) pressure.

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

- *Perched groundwater or a perched aquifer* – an unconfined lense 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 shallow depth, hydraulically unconnected to deeper, more laterally extensive unconfined or confined aquifers.

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

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

5.1.2 Types of groundwater flow

Groundwater flow is characterized as porous flow, conduit flow, fracture flow, or a combination of these types:

- *Porous flow* occurs through open, interconnected intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone, or unconsolidated deposit) or through intercrystalline pore spaces within igneous or metamorphic rock. The size of sediment grains or mineral crystals affects porous flow. Large pores between coarse grains (or crystals) are more conducive to flow than small pores between fine grains (or crystals) due to less friction with the lower relative surface area of larger pores. In an aquifer with a wide range of grain sizes (poorly sorted), the fine-grained material filling in the larger pore spaces reduces flow toward that of a fine-grained aquifer.

- *Conduit flow* occurs through large, discrete open spaces (pipes, cavities, channels, caverns, other karstic zones), generally within soluble sedimentary or evaporitic rocks (limestone, dolomite, salt). Conduits form by the dissolution of soluble minerals in bedrock or by subsurface sediment transport (piping) through unconsolidated or loosely consolidated material.

- *Fracture flow* occurs through interconnected partings in bedrock: fractures developed during structural deformation (folding, faulting); joints in rocks developed during expansion (with uplift and erosion) or compaction (cleats in coal); or fractures resulting from physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation). Fractures occur either along or across existing bedding planes or other types of geologic contacts.

5.1.3 Groundwater recharge, discharge, and flow

Groundwater systems at all scales, from a local unconfined aquifer in a Quaternary unconsolidated deposit to an entire groundwater basin, are characterized by the factors that determine recharge, storage, discharge, and flow to discharge areas.

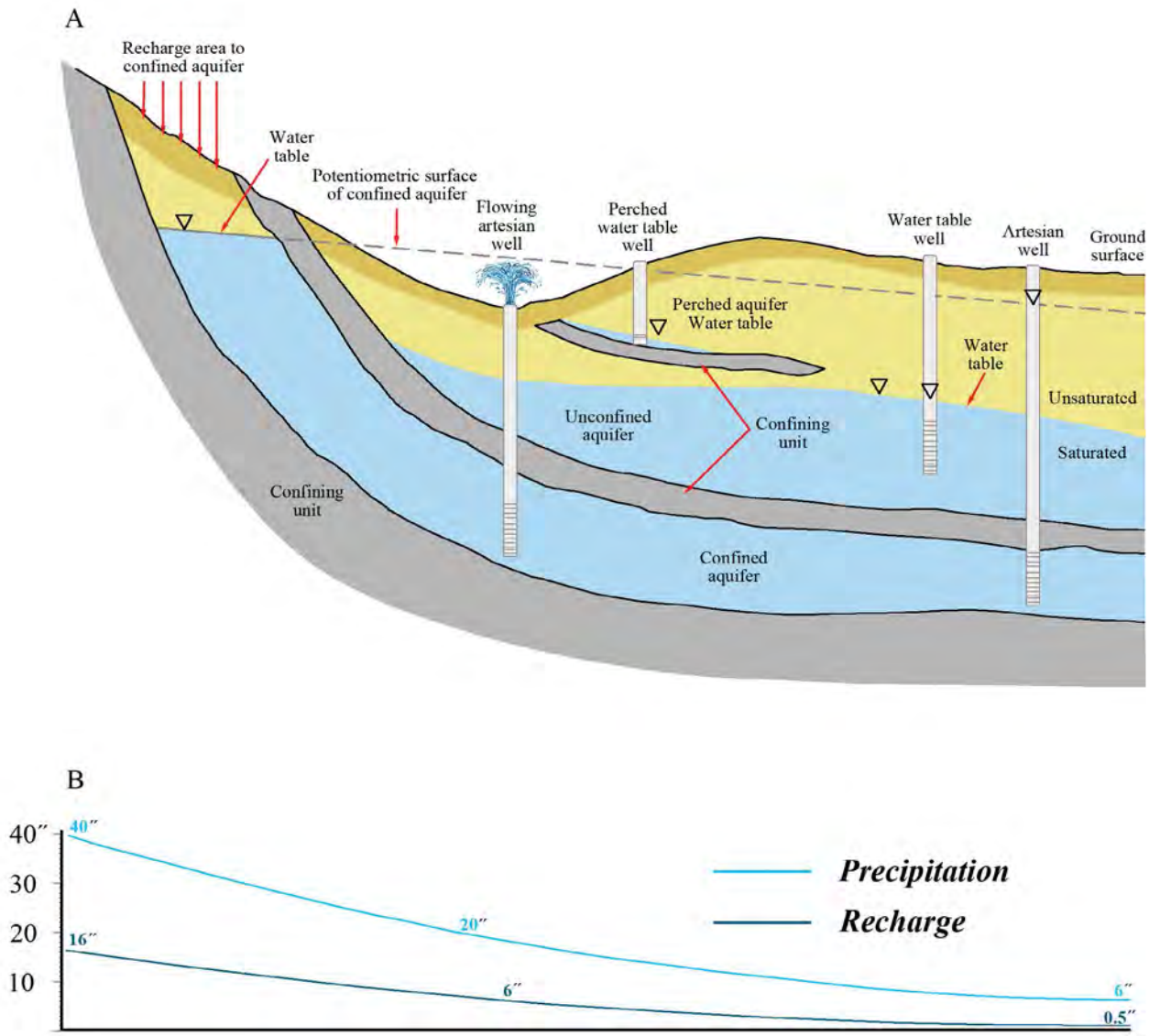


Figure 5-1. Conceptual cross section (adapted from WWC Engineering et al., 2007b) of groundwater features, basin margin to basin center: aquifer and confining unit cropping out and dipping into the basin, recharge confined and unconfined aquifer, water table and a potentiometric surface (triangles), a perched aquifer, and wells completed in unconfined and confined aquifer, including flowing and non-flowing artesian wells – as defined in this chapter. B. Idealized WBRB precipitation/recharge profile, in inches, basin margin to basin center.

5.1.3.1 Groundwater recharge

The accumulation of groundwater requires that an aquifer first be filled with water (charged), then refilled (recharged) to replace water lost. Recharge is a difficult parameter to determine; it cannot be measured directly but must be estimated from other measurements and determinations. Recharge is the amount of water that infiltrates the ground surface, percolates through the unsaturated zone, and reaches the water table – or leaks from adjacent aquifers or confining units. While recharge by leakage from or through confining units is very slow, it does occur if there is permeability and a pressure gradient into the receiving aquifer. Recharge from precipitation is generally expressed as the fraction (or percentage) of precipitation (in inches per year) that infiltrates the ground surface and reaches the water table. Recharge volume is estimated by multiplying estimated inches of recharge by the outcrop area of an aquifer. The *local* rate of infiltration varies on the basis of:

- Composition and hydraulic properties of the surficial materials (soil and underlying bedrock)
- Depth and degree of bedrock weathering
- Soil moisture
- Vegetation (type, abundance)
- Animal burrows, root zones
- Type, timing, rate, and duration of precipitation
- The difference between precipitation and evapotranspiration (ET) rates
- Slope and aspect of the land surface
- Depth and degree of bedrock fracturing
- Natural and man-made large-scale openings or depressions (caves, mines, pits)
- Opportunity for recharge from surface waters
- Local land use (irrigation, soil stripping, paved areas)
- Leakage from adjacent aquifers and/or confining units

Prior to infiltrating the subsurface, precipitation wets vegetation. Initially infiltrating water replaces any deficiency in soil moisture; then, available water percolates down through the unsaturated zone to the water table, below which saturated flow conditions prevail. The characteristics of the unsaturated zone affect the amount of water that reaches the water table. When precipitation exceeds the rate of infiltration, overland flow occurs; and additional recharge from surface flows may occur downstream from the site of precipitation. A common, very general assumption is that approximately 10 percent of precipitation recharges groundwater.

Artificial avenues of recharge include reservoirs, irrigation canals, injection wells and fields, infiltration galleries, unlined pits, and other surface water diversion projects, as well as flow between aquifers in poorly completed wells. (The extent of artificial recharge in the WBRB cannot be evaluated on a regional basis, but it might be determinable for a local area.)
In the fairly dry climate of Wyoming, most natural recharge (directly from precipitation) occurs in the mountain ranges surrounding the basins, on thick alluvial materials that border the mountain ranges, and along stream channels within and underlain by thick, permeable alluvial deposits. Most recharge in Wyoming occurs during late fall, winter, and early spring: vegetation is dormant, evapotranspiration is minimal, precipitation is generally higher, and snowpack functions as a reservoir maximizing contact with the ground surface and enhancing infiltration. In the central basin areas where the ET rate generally exceeds the precipitation rate, the opportunity for widespread recharge is limited to infrequent high precipitation and thick snowpack melting events. Recharge to bedrock within interior basin areas is also hindered by the generally flat-lying strata of the Tertiary hydrogeologic units, because permeability is generally less efficient across stratification.

For this study, a statewide quantitative evaluation of recharge prepared by the Spatial Data and Visualization Center (SDVC) for the *Wyoming Ground Water Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998) is utilized to evaluate recharge over the WBRB (Section 6.2.2). Average annual recharge to the WBRB, **Figure 5-2**, based on average annual precipitation from 1961 through 1990 and on published percolation percentages for documented soil/vegetation combinations, was generated as follows:

- Compile a map of soil/vegetation-combination unit boundaries with assigned recharge fraction values (percentages).
- Combine similar units.
- Overlay the average annual precipitation map and multiply recharge fraction by precipitation to calculate average annual recharge.

Hamerlinck and Arneson observed several common themes in the scientific literature on recharge:

- Recharge fraction (R/P) or percent of precipitation that reaches the uppermost aquifer in a given environment increases as depth to the water table decreases.
- Recharge fraction increases as precipitation increases.
- Recharge fraction increases as the sand content of the soil increases.
- Recharge fraction is higher in an above-average precipitation year and lower when precipitation is below average.
- Seasonal patterns and occurrences of major events like spring snowmelt alter the general effect of mean annual precipitation.

Hamerlinck and Arneson present additional discussion of how the recharge map presented in this study was developed and used for evaluating aquifer vulnerability. A discussion of other methods for determining recharge rates is beyond the scope of this study.

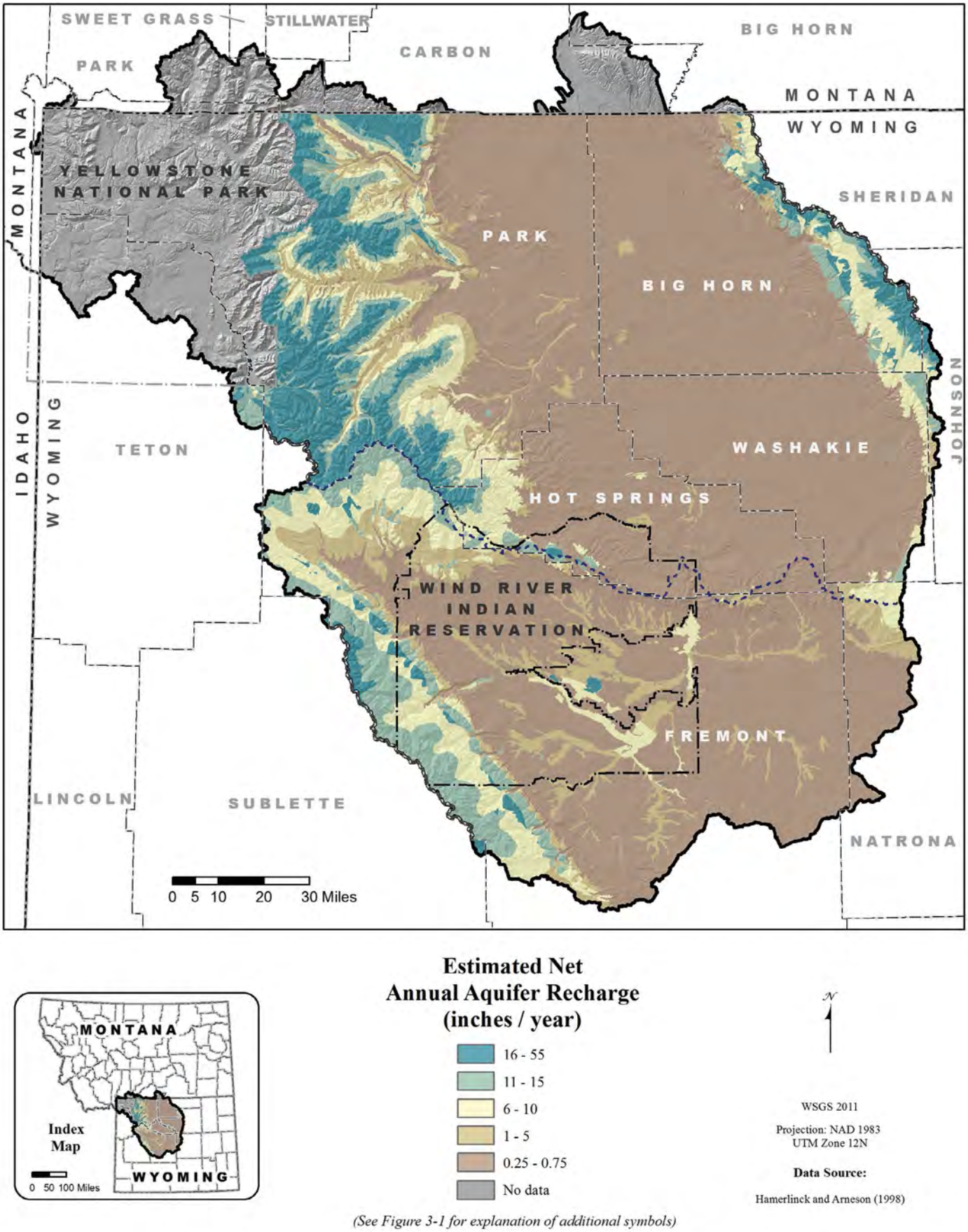


Figure 5-2. Estimated net annual aquifer recharge, Wyoming Wind/Bighorn River Basin.

5.1.3.2 Groundwater discharge

The natural discharge of groundwater in Wyoming basins includes leakage between geologic units; flow from springs; seepage into streams, wetlands, lakes and other surface waters, especially within thick alluvial deposits; and direct evaporation where the water table is shallow enough that capillarity or plant transpiration brings groundwater to the surface (evapotranspiration). Like recharge, natural discharge is difficult to determine, especially on a basin-wide basis, and cannot be measured directly but must be estimated from other measurements and determinations. Leakage between geologic units, which can be a significant part of natural discharge, occurs in the subsurface, and evapotranspiration and groundwater discharge to surface waters generally occur over large areas – these discharges cannot be measured and must be estimated.

In addition to wells, artificial avenues of groundwater discharge include seepage into mines, other excavations, irrigation canals, and drainage canals as well as flow between aquifers in poorly completed wells. In some areas of the WBRB, drainage tiles that discharge shallow groundwater directly to surface waters are installed in irrigated lands to lower the water table and prevent waterlogging and salt deposition. Groundwater withdrawals for beneficial use are estimated in the previous Water Plan (BRS Inc., 2003e) and current *Wind-Bighorn Basin Plan Update* (MWH et al., 2010) and are discussed in Chapter 8 of this memorandum.

Groundwater discharge, buffered by the storage function of an aquifer, is generally a more efficient process than recharge and occurs over a smaller area. While recharge occurs intermittently by water percolating through unsaturated material both across and parallel to stratification, discharge is a more continuous process that occurs under more efficient saturated flow conditions in the direction of highest hydraulic conductivity, generally parallel to stratification. Under natural conditions (no artificial discharge of groundwater) and over a time period that depends on the precipitation, hydrogeology, and hydrologic cycle in a groundwater basin, recharge and discharge are balanced. Reasonably accurate estimates of both recharge and discharge are necessary to evaluate safe/sustainable yield.

5.1.3.3 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. Gravity drives groundwater flow. The rate (velocity) of groundwater flow is determined by the hydrogeologic parameters (primarily permeability and gradient) of 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 deep aquifers of a groundwater basin. The saturated geologic units within a structural groundwater basin constitute the framework of groundwater flow.

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 in a gravel-rich, highly permeable aquifer 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 rock unit with very low to essentially no permeability may be less than a few inches every ten thousand years. Thus, flow rates through the various types of hydrogeologic units vary over 11 to 12 orders of magnitude. Folding, fracturing, and faulting modify the permeability and other hydraulic properties of both aquifers and confining units, and generally decrease 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 WBRB. Shallow, unconfined groundwater recharge, flow, and discharge in the WBRB are predominantly controlled by topography and stream drainage patterns. Local and regional shallow groundwater flow (less than 300-500 feet below the land surface) follows topography, is recharged by precipitation, and is discharged to streams and river drainages. Shallow groundwater flow in areas with hills, uplands, and high topographic relief is generally controlled by these local topographic features. 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 of base flow.

Groundwater and surface water are interconnected in the WBRB, as in all Wyoming basins. Discharge of groundwater to the surface may occur as described above from springs, subcrop discharge below and adjacent to surface waters, and wells. Surface water bodies recharge groundwater as permitted by the hydraulic gradient and characteristics of the underlying and adjacent earth materials.

Recharge of the deeper Paleozoic and Mesozoic aquifers in the WBRB occurs primarily where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeters of the structural basins. As groundwater flows downdip from the recharge areas into the structural basins, it becomes confined by low-permeability strata (shale, claystone) overlying and underlying the more permeable aquifers (sandstone, coal, fractured limestone and dolomite). Some recharge to deeper aquifers occurs as leakage from adjacent, usually underlying, hydrogeologic units. Some discharge occurs where recharge is rejected from fully saturated aquifers into headwater streams usually at the point where a stream intersects the contact between a confining unit and underlying

aquifer. Artesian groundwater flows at the land surface from wells completed in confined aquifers whose hydraulic pressure is greater than atmospheric pressure at the land surface.

Confined groundwater flow within the deeper bedrock formations of the structural basins and adjacent structural uplifts of the WBRB is commonly structurally and stratigraphically controlled. Major aquifers and aquifer systems in the WBRB occur predominantly within interstratified sequences of high- and low-permeability sedimentary beds. The WBRB aquifers are commonly heterogeneous and anisotropic on both local and regional scales. Deeper groundwater flow in the WBRB is predominantly through permeable formations down-gradient (from higher to lower hydraulic pressure) and generally down-dip toward the axes of the structural basins, and eventually northward into Montana.

Although groundwater flow is driven by gravity, the water does not always flow down hill, but from areas of higher pressure (greater hydraulic head) to areas of lower pressure (lower hydraulic head). In the deep subsurface, flow along any permeable vertical pathway is commonly from lower to higher elevation, as demonstrated by artesian wells and some springs that discharge groundwater from deep aquifers at the land surface. Groundwater flows in the directions indicated on potentiometric surface maps if permeable pathways exist; however, flow through preferential pathways (e.g., fractures) can depart from the maximum gradient direction. Hydraulic gradients are commonly steep in low-permeability geologic units where there is substantial resistance to flow (friction), and shallow (low-angle) to nearly horizontal within high-permeability units where resistance is low – analogous to a standing body of water, such as a pond, where there is no resistance to flow in any direction and the gradient due to gravity is flat.

5.1.4 Groundwater storage and safe/sustainable/optimal yield

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

To assess groundwater resources on either a local or a regional basis, both the total volume of groundwater present and the fraction of groundwater that can be accessed, developed at acceptable cost, and put to beneficial use should be determined. Technical, financial, and cultural factors determine what part of a total stored volume of groundwater can be considered an available resource; for example:

- Only part of the groundwater contained within an aquifer will be producible, and part will be retained within the aquifer. This issue is discussed in this section and in Chapter 6.

- The depth to the resource and other physical, cultural, legal, and institutional constraints may limit accessibility and preclude groundwater development due to cost or technical infeasibility. Various aspects of accessibility are addressed in Chapters 4 through 9.

- Groundwater must be of suitable quality to satisfy the requirements for its intended use. Groundwater quality is addressed in Section 5.6 and Chapter 7.

The amount of water that an aquifer will yield to natural drainage or to pumping is determined by its hydraulic properties. The basic hydraulic property with respect to sustainable yield is *effective porosity*, expressed as *specific yield* in unconfined aquifers and as *storage coefficient* in confined aquifers.

Specific yield applies only to unconfined aquifers; it is the amount of water that will drain (by gravity alone) from a saturated unit volume of rock expressed as a percent (or decimal fraction) of the unit volume. In an unconfined aquifer, specific yield is essentially the same as effective porosity. *Specific retention* is the volume of water that remains in the unit volume of rock after drainage, in isolated pores and attached to the aquifer matrix by molecular attraction and surface tension (capillarity). In an unconfined aquifer the sum of specific yield and specific retention equals *total porosity*. Because capillarity is higher in fine-grained materials (with smaller pore size and greater pore-surface area), it follows that coarser-grained aquifers generally have higher specific yield than finer-grained aquifers (even though finer-grained materials have higher total porosity than coarser-grained materials). Highly productive unconfined aquifers are characterized by high specific yield.

Storage coefficient applies to 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, and is expressed as percentage or (very small) decimal fraction. The mechanisms of releasing groundwater from unconfined and confined aquifers are very different. In an unconfined aquifer, water is released (drains) by gravity and the hydraulic head lowers. In a confined aquifer, water released from storage is from expansion of the water and compression of the aquifer rock matrix. Because the volume of water that can be produced due to these elastic properties is negligible in an unconfined aquifer, the effective porosity in an unconfined

aquifer is essentially equal to specific yield. Conversely, specific yield cannot be determined for a confined aquifer, but since water is released due to the elasticity of water and rock, the effective porosity is expressed as the storage coefficient. However, if the water level (hydraulic head) is reduced to the point that the confined aquifer becomes unconfined, then the effective porosity will be essentially equal to the specific yield. Pumping an aquifer to the extent that recharge is inadequate to maintain confined conditions is referred to as "mining the aquifer."

The stored water in an aquifer buffers recharge and discharge, allowing relatively constant production of groundwater during periods of variable recharge. Enormous volumes of water can be released from storage in a large aquifer from a relatively small persistent decline in hydraulic head, allowing continual withdrawal through periods of deficient recharge. Reflecting the difference between how water is released from storage in unconfined and confined aquifers, specific yields (in unconfined aquifers) are generally orders of magnitude larger than storage coefficients (in confined aquifers), and unconfined aquifers will yield substantially more water per unit decline in hydraulic head over a much smaller area than will 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 (e.g., through compression of a confined aquifer).

The terms "safe yield" and "sustainable yield" have been used to describe the rate of groundwater production that can be sustained without causing unacceptable depletion of storage (or excessive drawdown) or such other negative effects as degradation of groundwater quality or depletion of surface water flow. A safe/sustainable yield estimate predicts the response of an aquifer to long-term withdrawal. The concept of safe/sustainable yield can be applied over a wide range of scale, from individual wells to entire structural or drainage basins. Meinzer (1923, p. 55) defined the *safe yield* of an aquifer as *". . . the rate at which ground water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible."* However, other factors also must be considered in evaluating groundwater development prospects, such as ownership and other legal issues, environmental issues, potential for subsidence (confined aquifers), and interference with (or facilitation of) the development of other resources. Because groundwater has value only to the extent that it can be put to a beneficial use, perhaps "optimal yield" in the context of a range of options from deliberately depleting (mining) an aquifer (e.g., for CBNG development) to total conservation (e.g., for wetlands maintenance) may be a more useful concept than safe/sustainable yield.

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

$$\text{Recharge} - \text{Discharge} = \text{Change in storage}$$

Precipitation is the ultimate source of groundwater recharge, and both precipitation and recharge estimates have been mapped over the entire WBRB (**Figures 3-3 and 6-1**). Discharge is more difficult to estimate. Considered on the scale of a groundwater basin, discharge is essentially composed of natural discharge to surface water that is flowing out of the basin, subsurface groundwater flow out of the basin, evapotranspiration, and groundwater withdrawals (that are not returned to the groundwater system). Change in storage can be neutral (dynamic equilibrium), positive, or negative. This approach is applied over a wide range of data density, with analyses often based on rough estimates of the variables in the water balance equation, especially for basin-wide studies. Accordingly, the results reflect the variability of the estimates.

In the best case for groundwater development, the change in groundwater storage within a groundwater system where there is pre-existing withdrawal would be zero or increasing, with long-term average recharge adequate to prevent depletion of storage. It is tempting, and sometimes attempted, to estimate safe/sustainable yield as the amount of groundwater withdrawal that does not exceed average recharge (measured over the same time period). It is well known that this is not correct; however, the amount of water that can be withdrawn from a typical groundwater basin is fundamentally controlled by recharge, especially as withdrawal approaches or exceeds recharge. The water-balance equation shows that in addition to withdrawal, natural discharge also determines the amount of groundwater that is maintained in storage. The amount of water that can be withdrawn from a groundwater system (or an individual aquifer) that would not impact storage to an unacceptable degree might be defined as optimal yield – the portion of discharge that is not already being utilized (existing withdrawals, base flow to surface streams, etc.). Optimal development of all water resources of a basin would ultimately involve the conjunctive use of surface water and groundwater, especially where these resources are physically interconnected.

The unused or "available" part of natural discharge is difficult to determine, as data on natural discharge and groundwater withdrawals are generally (and for the WBRB) not adequate to perform an evaluation using the water balance approach.

The approach used in this study for evaluating groundwater resources (Section 6.2) is to consider average annual recharge over the areas of the aquifers exposed within WBRB, restrained by a best estimate of total discharge. Average annual recharge rates for the WBRB were estimated by the Spatial Data and Visulization Center (SDVC; Hamerlinck and Arneson, 1998) and are presented in **Figure 6-1** as developed from the SDVC data for this study. Based on the SDVC evaluation, annual recharge for specific aquifers and groups of aquifers is estimated and discussed in Section 6.2.2. A water balance for the WBRB including total annual precipitation, evapotranspiration/ groundwater recharge (presented as a combined value), surface water outflows, and groundwater withdrawn for beneficial use were estimated and presented in the previous Water Plan (WWDC, 2003) and current Wind-Bighorn Basin Plan Update (MWH et al., 2010). These data are compared with the aquifer-specific recharge estimates compiled for this study to estimate a range of "sustainable" groundwater resources available in the WBRB (Chapter 8 and 9).

The other aspect of the available groundwater resource that must be considered is the amount in storage; however, estimating the quantities of stored and potentially producible groundwater for an entire structural or drainage basin is also problematic. The available data are not adequate for estimating the quantities of groundwater stored within the individual hydrogeologic units or the aquifer systems in the WBRB. For this study very general estimates of porosity, yield and storage characteristics, and lithology are used to evaluate potentially producible groundwater resources at depths where quality and accessibility should not preclude development (Section 6.2.1).

The overall evaluation of the WBRB groundwater resource proceeded by calculations over the outcrop areas (Aquifers) of the WBRB defined in Section 6.2:

1. calculating the *total volume* of groundwater contained in the combined upper 1000 feet of the Tertiary and overlying Quaternary aquifers in the interior lowland basin areas (Q/T Aquifer and Quaternary Aquifer), estimated over a wide range of sand and coarser-grained lithology, by the equation

   Total groundwater volume = Land area × Saturated thickness × Porosity

2. calculating the volume of *potentially available* (producible) groundwater contained in the combined upper 1000 feet of the Quaternary-Tertiary aquifers (Q/T Aquifer and Quaternary Aquifer), estimated over a wide range of sand- and coarser-grained lithology and appropriate choices of storage functions, by the equation

   Available groundwater volume = Land area × Saturated thickness × Specific yield or storage coefficient

3. calculating average annual recharge to the Quaternary, combined Quaternary-Tertiary (in interior lowland basin areas), combined Mesozoic-Paleozoic, and Precambrian aquifers (Quaternary Aquifer, Q/T Aquifer, Mz/Pz Aquifer, p€ Aquifer) for the Wind River and Bighorn structural basins and to the Absaroka volcanic terrain (Absaroka Volcanics) of the Bighorn Basin, using the equation

   Annual recharge = Land area × Average recharge rate

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

Lithostratigraphic units are strata and other rock bodies distinguishable in the field on the basis of lithologic continuity and continuity of association – groups, formations, members, tongues, lenses – as named by geologists with the acknowledgement of the Geologic Names Committee of the U.S. Geological Survey. Examples are the Tertiary Wind River Formation and Indian Meadows Formation.

Plate I shows the surface geology of the WBRB mapped as geologic units.

Geologic units are scale-sensitive geologic map units. They correspond to lithostratigraphic units where a given map scale allows; and where two or more lithologic units occur together but are too thin or contorted or intermixed to map separately at that scale they are combined as a single, separate geologic unit. For example, three geologic units mapped separately on **Plate I** are the Wind River Formation (Twdr), Indian Meadows Formation (Tim), and Wind River and Indian Meadows Formations (Twim).

Plate IV shows the surface hydrogeology of the WBRB mapped as hydrogeologic units.

Hydrogeologic units are strata and other rock bodies distinguishable on the basis of hydrogeologic character and continuity of association – aquifers, aquifer systems, confining units – as defined in this report. Examples are the Wind River aquifer (Awr) and Indian Meadows confining unit (Cim). [The units that compose an aquifer or aquifer system in one area may have different hydrologic properties in another area that cause the hydrogeologic unit to be classified as an aquifer of a different class or as a confining unit: this difficulty is not accounted for on **Plate IV**.]

The correlation of WBRB lithogeologic, geologic, and hydrogeologic units is presented in this memorandum as follows:

Plates II and III show the correlation of geologic units that correspond to single lithostratigraphic units with hydrogeologic units in the Wind River Basin and Bighorn Basin. [These

geologic units are taken from the Stratigraphic Nomenclature Chart of Wyoming (Love et al., 1993), a reduction of the geologic units that correspond to single lithostratigraphic units on the 1985 Geologic Map of Wyoming, scale 1:500,000 (Love and Christiansen, 1985), which is the current defining source of Wyoming geologic units.] For example, on **Plate II** the Wind River Formation correlates with the Wind River aquifer and the Indian Meadows Formation correlates with the Indian Meadows confining unit. [**Plates II and III** also show corresponding WBRB hydrogeologic classifications proposed in previous studies and the Wyoming Statewide Framework Water Plan (WWC Engineering, 2007).]

Plate V charts the correlation of all WBRB geologic units on **Plate I** with their constituent lithostratigraphic units and with the hydrogeologic units on **Plates II, III, and IV**. Because hydrogeologic units are presented in terms of geologic units that correspond to single lithostratigraphic units, those geologic units that correspond to combined lithostratigraphic units are not accounted for on **Plates II and III**: they are presented on **Plate V** as "undifferentiated geologic units." For example, on **Plate V** the Wind River and Indian Meadows Formations (Twim) geologic unit correlates with an "undifferentiated Tertiary hydrogeologic unit" in the WRB.

On **Plate V** also, those geologic units representing lithostratigraphic units whose hydrogeologic character is not defined are presented as "undefined hydrogeologic units." For example, on **Plate V** the Tertiary Tatman Formation (Tta) geologic unit correlates with an "undefined Tertiary hydrogeologic unit" in the BHB. **Plate V** thus shows generally how the geologic units on Plate I are accounted for on **Plate IV.**

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering, 2007) proposed a generalized classification scheme for the entire state based on how much water an aquifer can be expected to provide for beneficial use, based on historical records. Individual geologic units were assigned to seven categories based on their hydrogeologic characteristics as developed in the original individual Basin Plans:

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 WBRB; under favorable conditions they can provide well yields of 500-1,000 gallons per minute (gpm). Flow through unconsolidated material occurs through primary intergranular porosity (porous flow). In areas where the deposits are thin, contain abundant fine-grained material, or are at higher elevations and isolated from active streams (e.g., terrace deposits), yields are generally low. Where the alluvial aquifer is in contact with an active stream, direct infiltration from the stream may provide most of the groundwater in storage. Where surface streams are the primary source of groundwater, alluvial aquifer water quality generally reflects the water quality of the stream, as modified by the composition of the aquifer matrix. Where discharge from shallow bedrock aquifers is a primary source of alluvial-aquifer recharge, water quality is similarly influenced.

Major aquifer – sandstone: These consolidated bedrock formations, composed primarily of permeable sandstone, conglomerate, and other coarse-grained lithologies, commonly supply groundwater; some have the potential to yield large quantities of good-quality groundwater. Porous flow is generally dominant; however, fracture flow can be significant in structurally deformed areas. Within the interior lowland basin areas, the sandstone aquifers are mostly horizontal, and some are widespread. Relatively thick Tertiary sandstone sequences of the Wind River Formation are the most productive sandstone aquifers in the WBRB. Older Mesozoic and Paleozoic sandstone aquifers exposed around the perimeters of the WBRB structural basins commonly dip into the basins (**Plate IV and VI**) and may host accessible groundwater resources for several miles basinward of the outcrop areas. Groundwater quality tends to decrease with increasing depth into the basins. Sandstone aquifers can exhibit poor yield where they are locally heterogeneous, contain fine-grained material, are cemented, or lack fractures. Discontinuous layers and lenses of sandstone (and coarser lithologies) are generally the most productive intervals; however, coal beds and other strata can also yield substantial groundwater. Where sandstone layers are not thick and widespread but rather are heterogeneous and discontinuous, wells must penetrate several individual water-bearing layers to provide flow adequate for an intended use.

Major aquifer – limestone: These consolidated bedrock formations are composed primarily of Paleozoic carbonate rocks (limestone or dolomite) and have various potential for development, ranging from areas with very low yield to areas yielding large quantities of good-quality water. Localized areas of vigorous groundwater flow and high productivity are due to enhanced permeability developed along solution-enlarged fractures caused by deformation and groundwater circulation. These aquifers are exposed primarily along the structural basin margins in the WBRB (**Plate IV**), where deformation and potential for vigorous recharge and groundwater circulation are most prevalent. Examples include the Madison Limestone, the Casper Formation, and the Bighorn Dolomite. The most productive well in Wyoming is a flowing well completed in the Madison Limestone at the crest of the Paintrock Anticline north of Worland that yields more than 10,000 gpm of drinking-quality water. Depending on enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles basinward of their outcrop areas; however, they generally are more deeply buried than the overlying sandstone aquifers progressing into the basins, and

access to them becomes increasingly difficult with depth.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). Yields greater than 50 gpm are available at some locations, a function of the local hydrogeologic characteristics and recharge. Water quality in the minor aquifers varies from good to poor. The minor aquifers are typically thinner, more heterogeneous, have lower yield, and are less laterally extensive than the major aquifers. Similarly to the other aquifer types, areas in and near outcrop are characterized by generally better circulation and groundwater quality, both of which deteriorate 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 very favorable local conditions. The permeability of marginal aquifers is generally low enough that 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 act to hydraulically separate underlying from overlying aquifers, commonly on a regional scale. These are some of thickest and most widespread formations in Wyoming. Because of their high clay content, these strata are generally less brittle than other lithologies and therefore less subject to the 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 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 have fracture permeability that sustains springs and low-yield wells that generally 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, 2007) classified the WBRB geologic units as follows:

Major Aquifer - Alluvial

Quaternary alluvium

Major Aquifer - Sandstone

Wind River Formation (Wasatch/Willwood Formations equivalent)

Major Aquifer - Limestone

Tensleep Sandstone
Madison Limestone and Bighorn Dolomite
Flathead Sandstone

Minor Aquifer

Quaternary non-alluvial deposits
Willwood Formation in Bighorn Basin (Wasatch/ Wind River Formations equiv.)
Fort Union Formation
Lance Formation and Fox Hills Sandstone
Mesaverde Formation or Group
Frontier Formation
Cloverly (Dakota) Formation and Morrison Formation
Sundance Formation, Nugget Sandstone, and related units
Phosphoria Formation and related units (Goose Egg Formation equivalent)
Bighorn Dolomite and Flathead Sandstone

Marginal Aquifer

Quaternary deposits
Quaternary and Tertiary volcanic rocks
Wagon Bed Formation in Wind River Basin; Crandall Conglomerate in Bighorn Basin (T56N, R108W, Park County)
Chugwater Formation or Group and related units
Amsden Formation

Major Aquitard (Confining Unit)

Indian Meadows Formation in the Wind River Basin (Eocene age, located above Fort Union Formation and older than Wind River Formation)
Meeteetse Formation and Lewis Shale
Cody Shale (and equivalent Steele Shale and Niobrara Formation in southern Wind River Basin)
Thermopolis Shale and Mowry 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 hydrogeological detail and analysis. **Plate IV** outlines the hydrogeology developed in this Memorandum for the WBRB. How the WWC Engineering (2007) statewide classification system correlates with the hydrogeology presented in this study is depicted on **Plates II and III**.

5.4 Influence of structure on groundwater circulation

Huntoon (1993) summarized a conceptual model for *"The influence of Laramide foreland structure on modern ground-water circulation in Wyoming artesian basins"* that he and several graduate students (p. 786) at the University of Wyoming developed over several years of research and field work, largely within the Bighorn Basin. The central thesis of their research is that large-displacement thrust faults, reverse-fault-cored anticlines, and associated fractures and anisotropic permeability that developed during Laramide compressional deformation strongly influence groundwater recharge and circulation through the Paleozoic carbonate aquifers exposed along the major uplifts of the Wyoming foreland basins. Components of this conceptual model are as follows.

- The Wyoming foreland mountain ranges are large-scale uplifts atop large-displacement (thousands of feet) basement thrust faults with a fault-severed margin on one side and homoclinal dip on the other. Some of the cross sections on **Plate VI** show this Laramide structural pattern: crustal shortening from compressional tectonic forces is clearly illustrated.

- Horizontal compression and crustal shortening during the Laramide Orogeny that shaped the basins is also reflected in smaller structures within the basins (e.g., reverse- and thrust-cored asymmetric anticlines).

- Laramide deformation and erosion established the hydraulic boundaries of groundwater circulation in Wyoming's foreland structural basins.

- Groundwater circulation is both enhanced and diminished by the deformation of the aquifers:
    - Fracture permeability within carbonate strata associated with faulting and folding is enhanced by carbonate dissolution.
    - Generally, any fracture can potentially enhance permeability, even if formed in a compressional environment (e.g., trough of a synclinal fold).
    - Fractures along and parallel or oblique to the crests of folds, together with bedding-plane fractures, formed during anticlinal folding. These fractures are extensional and have maximum potential for developing solution-enhanced, highly anisotropic permeability. Where it develops, extensional fracture permeability dominates local groundwater circulation. Groundwater circulation within areas of highly anisotropic fracture permeability along the crests of anticlinal folds is inhibited across the structural trend and tends to converge within the fractures developed along and parallel or oblique to the folds.
    - Large-displacement thrust faults and smaller displacement reverse and normal faults can sever an aquifer's hydraulic connection between recharge areas and the deeper basin interior. Separate groundwater circulation systems develop in the hanging wall and the footwall of major uplift-bounding, large-displacement faults.
    - Within synclinal folds the rocks are highly compressed, out-of-synclinal thrusting thins the strata, interstitial porosity is destroyed, and fractures are compressed rather than open.
    - Faults can act as either conduits or barriers to flow.

- Karst developed along pre-existing fractures within 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 Laramide basins.

- To a lesser extent, paleokarst developed when the Paleozoic carbonate strata were exposed during Late Mississippian time has enhanced permeability; however, the paleokarst has largely been filled in with sediments that reduce permeability.

- Where permeability is not enhanced by solution-enlarged fractures, which includes by far most of the subsurface extent of the Paleozoic carbonate aquifers, intercrystalline permeability is very low.

- Groundwater circulation in Wyoming basins is primarily parallel to bedding. Vertical circulation within the deep artesian basins is very limited except along faulted and fractured anticlines where the permeability of confining units is enhanced (e.g., at Thermopolis Hot Springs).

- Brittle strata (sandstone, limestone, dolomite) are more prone to fracture during deformation than fine-grained strata (shale, claystone, mudstone). Fine-grained strata are also more plastic, and small fractures within these units tend to close and seal under compaction.

- Artesian pressure within the basins increases with depth as the recharge areas of the deeper Paleozoic aquifers are exposed at generally higher elevations in the surrounding mountain ranges.
- Large production from the Madison aquifer 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 the Paleozoic strata 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 for solution-enhanced permeability and therefore accept less recharge. With less groundwater circulation, dissolution-enhanced permeability in recharge areas is discontinuous into the basins due to diagenetic effects (compaction, cementation, recrystallization) that destroy porosity and permeability; therefore, transmissivity decreases basinward, and recharge is rejected at springs at the base of the mountains, generally near the location where the carbonate aquifers are first covered by a significant confining unit. The difference in diagenetic conditions between recharge areas and the basins increases over time proportional to groundwater circulation (more circulation causes increased dissolution). Nevertheless, homoclinal areas where a carbonate aquifers exhibit significant karstification may be favorable groundwater development prospects.

- Groundwater in the Paleozoic aquifers at homoclinal basin margins is generally of good quality, and high yields can be obtained under the right conditions; however, in areas where rejected recharge is occurring, surface water and groundwater are clearly interconnected.

- Updip areas of the Paleozoic aquifers may be only partially or intermittently saturated, and greater topographic relief may limit access to optimal drilling locations (tops of anticlines, adjacent to faults).

- The characteristics that make local exposures of the carbonate aquifers optimal for recharge (good exposures, fracture permeability) also make them highly vulnerable to contamination.

- The synclinal areas of folds and the footwall sides of fault-severed aquifers are not good prospects for groundwater development.

- Computer models of the Paleozoic aquifers (and petroleum reservoirs) in the Wyoming foreland basins must account for the highly anisotropic trends of permeability and transmissivity to accurately predict yield, drawdown, and other production characteristics.

The conceptual model described above has obvious implications for groundwater exploration and development, and these concepts have been utilized in groundwater development projects throughout the state: **Appendix B** lists WWDC projects that have implemented this exploration model. Clearly, identifying and mapping structures in prospects involving the Paleozoic carbonate aquifers would be an important aspect of any groundwater exploration project in the WBRB. Groundwater circulation in the Paleozoic aquifer system of the Bighorn Basin is discussed further in Section 7.2.7.5, and several of the components of the conceptual model described above are illustrated in **Frontpiece figure and Figure 5-1**.

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

A generalized conceptual model of deep groundwater circulation within a typical Rocky Mountain Laramide structural basin (Richter, 1981) proposed flow within all aquifers down to the Precambrian basement surface, extending from outcrop areas on the basin flanks to the center of the basin and thence upward toward ground surface, and a strong vertical gradient developing with progressive flow into the basin. However, over the past three decades, oil and gas geologists and engineers have developed several generally similar exploration models, variously referred to as "Basin Centered Gas Systems" (BCGSs), "Deep Basin Gas Systems," "Tight Gas Systems," and "Continuous Gas Systems," to name a few of the most popular (Shanley et al., 2004), that preclude Richter's older groundwater-flow model.

The relevant hydrogeologic aspect of BCGS models is that the deeper volumes of Rocky Mountain Laramide basins, and other basins worldwide, are characterized by multi-phase flow systems where, in addition to water and occasionally liquid hydrocarbons, the strata are regionally and continuously saturated with natural gas, often at anomalous (relative to hydrostatic) pressure. Within these multi-phase flow systems, as the proportion of gas and liquid hydrocarbon phases increases, the permeability to water (generally brine) decreases, until groundwater essentially will not flow. This condition, commonly referred to as "irreducible water saturation," is consistent with the typically very low production of water from BCGS reservoirs, especially fine-grained reservoirs, experienced by oil and gas producers. Within BCGSs, groundwater can be essentially immobile over a wide range of conditions even where it is a significant fraction of the fluid occupying the pore space, especially in low-permeability rocks. In multi-phase flow systems, permeability relationships are complex and generally

lower for all fluids in proportion to their percent saturation of the total fluid. Heterogeneous lithology is commonly associated with patchy saturation.

Surdam et al. (2005) summarize the BCGS conceptual model and the following characteristics common to these hydrocarbon systems:

- Anomalously pressured (both high and low) compartmentalized BCGS reservoirs are separated from the overlying normally (hydrostatic) pressured, single-phase, meteoric groundwater-flow system by a regional pressure surface boundary.

- There is a significant change in water chemistry and thermal regime across the surface: below the surface, meteoric flow is precluded, water quality declines (toward brine composition), and temperature increases along the geothermal gradient. Higher temperatures enable increased dissolution of rock matrix minerals and lower water quality.

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

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

In light of the BCGS and the conceptual model for groundwater circulation along basin margins (Section 5.4), the evaluation of WBRB groundwater resources based on recharge and storage calculations proposed in this memorandum (Section 6.2) is a plausible approach, considering the limited amount of data available relative to the size and diversity of the WBRB hydrogeologic regime.

5.6 Natural groundwater quality and hydrogeochemistry – General discussion

The availability of groundwater depends on hydrologic, technical, legal, institutional, and cultural factors. Demand, feasibility of development, and potential uses for groundwater depend on water quality. Groundwater quality data, available for the WBRB hydrogeologic units from a variety of sources (Section 5.6.1), was compiled for this study by the U.S. Geological Survey. The data confirms that the best quality groundwater is generally found closest to the recharge areas, and that quality is modified by a variety of chemical reactions while infiltrating through the soil horizon, percolating through the vadose zone, and circulating through or residing in the aquifers. Factors that affect groundwater quality include the vegetation in recharge areas and local lithology (mineral composition), grain size, transmissivity, rate of circulation, and temperature in the aquifers. This generalization is more applicable to the "minor" and "marginal" aquifers of the WBRB than to the "major aquifers," within which groundwater circulation is relatively (often substantially) more vigorous.

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

Bedrock aquifers receive recharge through infiltration of precipitation, by discharge from adjacent bedrock and alluvial formations, and from surface waters (including irrigation). In general, in the absence of natural surface water or irrigation, recharge is dominated by precipitation in outcrop areas.

Recharge from surface water is more prevalent near streams and associated saturated alluvial deposits, but discharge from bedrock to streams that supports base flow is common throughout the WBRB. 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, with calcium-bicarbonate type water dominant in recharge areas and with sodium increasing relative to calcium and sulfate and chloride dominant over bicarbonate in deeper aquifers. In general, groundwater quality tends to be better in more productive bedrock aquifers because more active groundwater circulation provides less time for dissolution of minerals.

5.6.1 Groundwater quality (Timothy T. Bartos)

This section describes groundwater quality for the Wind River Basin, the Bighorn Basin, and the Absaroka Range and Yellowstone volcanic area. Specifically, this section addresses how data on chemical constituents for the Wind River/Bighorn Basin groundwater study were compiled, accessed, screened, and statistically summarized. Discussion of the physical and chemical characteristics of the hydrogeologic units defined for this study (Plates II and III) is found in Chapter 7.

5.6.1.1 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* (Wyoming Department of Environmental Quality, 1993), 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.

5.6.1.2 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 (**Table 5-1**) and summary statistics for environmental water samples tabulated by hydrogeologic unit as quantile values (**Appendices E and F**). In assessing suitability for domestic use (Wyoming Class I groundwater), USEPA health-based standards of Maximum Contaminant Levels (MCLs) and Health Advisory Levels (HALs) are used (however, these standards are not legally enforceable for any of the sampling sites used in this study). USEPA Secondary Maximum Contaminant Levels (SMCLs), which generally are aesthetic standards for domestic use, and WDEQ Class II groundwater standards for agriculture and Class III standards for livestock 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 is measured against three types of USEPA standards: Maximum Contaminate Level (MCL), Secondary Maximum Contaminant Level (SMCL), and Lifetime Health advisory (HAL) standards.

- The USEPA MCLs (U.S. Environmental Protection Agency, 2006) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections, or regularly serve at least 25 individuals.

The purpose of MCLs is to protect public health by limiting the levels of contaminants in drinking water. MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. They are, however, a valuable reference when assessing the suitability of water for these uses.

- USEPA SMCLs (U.S. Environmental Protection Agency, 2006) are non-enforceable guidelines regulating contaminants in drinking water that may cause cosmetic effects (such as skin or tooth discoloration) or have negative aesthetic effects (such as taste, odor, or color) in drinking water.

- USEPA 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, 2006). 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.

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.

5.6.1.3 Sources, screening, and selection of data

Groundwater-quality data were gathered from the USGS National Water Information System (NWIS) database,

http://waterdata.usgs.gov/wy/nwis/qw/

the USGS Produced Waters Database (PWD), the Wyoming Oil and Gas Conservation Commission (WOGCC) database, the University of Wyoming Water Resources Data System (WRDS) database, and other sources such as consultant reports prepared in relation to development of public water supplies. Methods used to screen data differ among the data sources, but the overall objective of all screening was to identify and remove samples that (1) were duplicates; (2) were not assigned to hydrogeologic units or were assigned to hydrogeologic units that contradicted local geologic information, particularly for shallow wells; (3) had inconsistent water-chemistry information such as poor ion balances or substantially different values of total dissolved solids and the sum of major ions; or (4) were unlikely to represent the water quality of a hydrogeologic unit because of known anthropogenic effects; for example, samples from wells monitoring known or potential point-source contamination sites or mining spoils sites. Groundwater-quality sample locations retained after data screening, and used herein, are shown in **Figure 7-1**.

Many of the groundwater sites in the Wind River and Bighorn Basins had been sampled more than once; however, only one groundwater sample from a given site was selected for this study, to avoid biasing the statistical results in favor of multiple-sample sites. An exception involved some sets of PWD samples from the same well at different depths and from different hydrogeologic units. In choosing among multiple samples from a site or well/hydrogeologic-unit combination, either the most recent sample, the sample with the best ion balance, or the sample with the most complete analysis was retained in the final dataset.

Chemical analyses of groundwater-quality samples available from the USGS PWD http://energy.cr.usgs.gov/prov/prodwat/ 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 Wind River and Bighorn Basins. 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. 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 WOGCC database http://wogcc.state.wy.us/ were included in the dataset used for this report. Major-ion balances were calculated for these samples. Samples with an ion balance of greater than 10 percent generally were removed from the

Table 5-1. Selected groundwater quality standards and advisories
[MCL, maximum contaminant 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; 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 and standards				
		Domestic[1]			Agricultural[2]	Livestock[2]
		MCL (USEPA)	SMCL (USEPA)	HAL (USEPA)	Class II (WDEQ/WQD)	Class III (WDEQ/WQD)
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
	SAR (ratio)				8	
Trace elements (µg/L)	aluminum (Al) (range)		50–200		5,000	5,000
	antimony (Sb)	0.6				
	arsenic (As)	10			100	200
	barium (Ba)	2,000				
	beryllium (Be)	4			100	
	boron (B)			1,000	750	5,000
	cadmium (Cd)	5			10	50
	chromium (Cr)	100			100	50
	cobalt (Co)				50	1,000
	copper (Cu)	1,300	1,000		200	500
	cyanide[3] (CN^-)	200				
	iron (Fe)		300		5,000	
	lead (Pb)	15			5,000	100
	lithium (Li)				2,500	
	manganese (Mn)		50		200	
	molybdenum (Mo)			40		
	mercury (Hg)	2				0.1
	nickel (Ni)			100	200	
	selenium (Se)	50			20	50
	silver (Ag)		100			
	thallium (Tl)			0.5		
	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					100
	ammonium (NH_4^+)			30		

Table 5-1. Continued. Selected groundwater quality standards and advisories
[MCL, maximum contaminant 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; 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 and standards				
		Domestic[1]			Agricultural[2]	Livestock[2]
		MCL (USEPA)	SMCL (USEPA)	HAL (USEPA)	Class II (WDEQ/WQD)	Class III (WDEQ/WQD)
Radiochemicals (pCi/L)	gross-alpha radioactivity[4]	15			15	15
	strontium-90 (strontium)			4,000 (mg/L)	8	8
	radium-226 plus radium-228				5	5
	radon-222 (radon)[5]	300/4,000 (proposed)[5]				
	uranium (µg/L)	30				

[1] Selected from USEPA 2006 edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2006)

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

[3] Trace ion, included for convenience.

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

dataset, but some samples with an ion balance of between 10 and 15 percent from areas with few samples were retained.

Chemical analyses of groundwater-quality samples available from the WRDS database http://www.wrds.uwyo.edu/ were included in the dataset used for this report for samples for which information was available to identify the hydrogeologic unit and locate the spring or well and if 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 Wind River and Bighorn Basins 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.

Many 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 Cretaceous-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.

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

5.6.1.4 Water-quality characteristics

The total dissolved solids (TDS) concentration in groundwater tends to be high with respect to the USEPA SMCL in most

of the Wind River and Bighorn Basins, 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, 2006). 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	0–1,000 mg/L
Slightly saline	1,000–3,000 mg/L
Moderately saline	3,000–10,000 mg/L
Very saline	10,000–35,000 mg/L
Briny	more than 35,000 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, 1989). 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 Wind River and Bighorn Basins 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, 2006) and WDEQ groundwater-quality standards

http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf

As expected, concentrations in produced-water samples (defined in a following section, "Produced-Water Samples") commonly exceeded many USEPA and WDEQ standards.

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2006). 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.

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, 2006; Bohn and others, 1985, and references therein). The USEPA 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.

High fluoride concentrations commonly are associated with produced water from deep hydrogeologic units in sedimentary structural basins. Low concentrations of fluoride in the diet have been shown to promote dental health, but higher doses can cause health problems such as dental fluorosis—a discoloring and pitting of the teeth—and bone disease (U.S. Environmental Protection Agency, 2006). 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, 2006). 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).

5.6.1.5 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 Wind River and Bighorn Basins. **Supplementary data tables** contain all the data used in this chapter – data too numerous for inclusion in the report, but available online at

http://waterplan.state.wy.us/plan/windbig/

From these data, *summary statistics* were derived for physical properties and major-ion chemistry of groundwater in hydrogeologic units in the Wind River and Bighorn Basins, as tabulated in **Appendix E** for environmental samples and **Appendix F** for produced-water samples. *Environmental water* is natural groundwater as produced from wellheads and springs; it is not associated with hydrocarbons. *Produced water* is water

co-produced (pumped out of the ground) with oil and gas. The water-quality data for the hydrogeologic units in the Wind River and Bighorn Basins also are compared to USEPA and WDEQ standards for various water uses, as the *groundwater-quality standard exceedance frequencies* presented in this report.

Groundwater-quality-standard exceedance frequencies are reported as a percentage, which is based on the number of samples analyzed for the physical property or constituent, not the total number of samples available in the dataset for the hydrogeologic unit. For some constituents, groundwater-quality datasets used for calculation of summary statistics were different than the final datasets used for calculation of groundwater-quality-standard exceedance frequencies. All groundwater-quality samples and analyses in the final datasets were used for calculation of groundwater-quality- standard exceedance frequencies. Several laboratories analyzed samples included in the dataset for this report, and many different types of analyses and analytical methods were used for the same constituent in the final datasets. Many results were considered appropriate for calculation of exceedance frequencies after the initial data screening described previously in the "Sources, Screening, and Selection of Data" section. After additional review of available laboratory quality-control documentation, some chemical analyses were considered incompatible for use in summary statistics. Selected data from laboratories were removed after the review. In some cases, the additional review of the final datasets resulted in a smaller number of samples for a given constituent being used for calculation of summary statistics than were used for calculation of exceedance frequencies, or resulted in some constituents being compared with exceedance frequencies and not used for calculation of summary statistics. For example, some values that exceeded groundwater-quality standards are not shown in the summary statistics appendices; however, all data are shown in the supplementary data tables. In addition, groundwater quality datasets used for calculation of summary statistics for constituents with censored values (described in the following paragraph) may have been different than the final datasets used for calculation of groundwater-quality standard exceedance frequencies because of the sample size requirements for the statistical method selected for calculation of summary statistics (see following paragraphs). All groundwater-quality samples and analyses in the final datasets were used for calculation of groundwater-quality-standard exceedance frequencies, including hydrogeologic units with less than four samples or less than three uncensored values for a constituent. Because the statistical method selected only computes statistics for the interquartile range, large values that may have exceeded groundwater-quality standards may not be shown in the summary statistics tables (**Appendices E and F**).

Statistical tabulation of physical properties, major-ion chemistry, and trace elements are presented in **Appendices E and F**, whereas nutrients and radiochemical constituents are presented only in **Appendix E**. Standard summary statistics (Helsel and Hirsch, 1992) for uncensored data were used for physical properties and major-ion chemistry. Censored data are values reported as greater or less than a threshold, such as "less than the detection limit" or "less than 1 mg/L." For a few samples, censored values ("less-than") were used in the calculation of summary statistics. These values were treated as concentrations equal to the laboratory reporting limit. For a sample size of 1, only a minimum value is presented in **Appendices E and F**; for a sample size of 2, minimum and maximum values are presented; for a sample size of 3, minimum, median (50th percentile), and maximum values are presented; for sample sizes of 4 or more, minimum, 25th percentile, median (50th percentile), 75th percentile, and maximum values are presented.

Chemical analyses available for many nutrient, trace element, and radiochemical concentrations were reported as censored values. In some cases, censored values contained multiple detection limits (MDL). A statistical technique that computes summary statistics for MDL data (or left-censored data) was used to analyze such data in this report. Rather than assigning the laboratory reporting limit or another arbitrary limit to the values, censored-value analysis was used to compute summary statistics. For some constituent analyses, values of "0" were included in the original dataset. During the additional review of the datasets, it was determined that these zero values probably were associated with missing or censored values. Because a laboratory reporting limit was not stored in the original database for these samples, the zero values were removed from the dataset before calculation of summary statistics.

Regression-on-order statistics of log-transformed data and the adjusted maximum likelihood estimation (AMLE) of Cohn (1988) are two methods designed to reduce the error of estimation during statistical summary of censored data (Helsel and Cohn, 1988). For this report, the AMLE method was selected because it yields the lowest errors for quartiles compared to other methods (Helsel and Cohn, 1988, p. 1997). The AMLE method computes statistics for the interquartile range for the dataset; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, and 75th percentile. The AMLE method requires a sample size of four samples or greater and at least three values must be uncensored for any sample size in order to compute percentiles; thus, summary statistics are only presented for hydrogeologic units that met these criteria. Generally, the method is more reliable for large sample sizes compared to small sample sizes.

Because of the sample size requirements for calculating statistics with the AMLE method, groundwater-quality datasets used for calculation of summary statistics for constituents with censored values may have been different than the final datasets used

for calculation of groundwater-quality-standard exceedance frequencies. All groundwater-quality samples and analyses in the final datasets were used for calculation of regulatory standard exceedance frequencies, including hydrogeologic units with less than four samples or less than three uncensored values for a constituent. Because the AMLE method only computes statistics for the interquartile range, large values that may have exceeded regulatory standards may not be shown in the summary statistics tables.

5.6.1.5.1 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) and specific conductance (reported in microsiemens per centimeter at 25 degrees Celsius). 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 potassium, sodium-adsorption ratio (calculated), dissolved sodium, alkalinity (reported as calcium carbonate), dissolved bromide, dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and total dissolved solids.

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. 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), and dissolved phosphorus (reported as phosphorus). In addition, total phosphorus (reported as phosphorus), analyzed in a laboratory using unfiltered water samples, also was included in the summary statistics. These constituents are reported in milligrams per liter. All nutrient constituents, regardless of method or reporting form, were included in the final datasets that were used for calculation of groundwater-quality standard exceedance frequencies; therefore, a value may be listed in the exceedance frequency tables (available online at URL to be provided by WRDS/WSGS) but is not listed in the summary statistics tables.

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, bromine, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, selenium, silver, strontium, thallium, 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 waters, that were included in the datasets for this report were dissolved alpha radioactivity (using thorium-230 curve method), gross beta radioactivity, dissolved radium-226, dissolved radium-226 (using a radon method), dissolved radium-228, dissolved uranium (natural), radon-222 (unfiltered) (referred to herein as "radon"), and tritium (unfiltered). All radiochemical constituents are reported as picocuries per liter (pCi/L) except uranium, which is reported as micrograms per liter (µg/L).

5.6.1.5.2 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 WOGCC database and the USGS PWD. The physical properties and constituents presented in this report for produced-water samples are pH, major ions, and trace elements. Nutrients were not included because nitrate was the only constituent available; it was infrequently reported

in the sample analyses, and the form (whether as nitrate or as nitrogen) was not reported. Radiochemical data were used to calculate exceedance frequencies, but were not used to calculate summary statistics because radium-226 was the only constituent available; it was infrequently reported with the sample analyses, and the reporting units were unknown.

The physical properties, major ion chemistry, and trace elements summarized for produced waters 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 statistically analyzed herein are pH (in standard units), conductance (assumed to be specific conductance reported in microsiemens per centimeter at 25 degrees Celsius), calcium, magnesium, potassium, sodium-adsorption ratio (calculated), sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, fluoride, silica, sulfate, and dissolved solids. The method for determining concentrations of total dissolved solids was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter. The trace elements summarized comprise aluminum, arsenic, barium, boron, copper, iron, lead, lithium, manganese, molybdenum, nickel, selenium, strontium, and zinc. Trace-element concentrations in the original database were reported in milligrams per liter; concentrations were converted to micrograms per liter for the statistical summary.

5.6.1.6 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Wind River-Bighorn Basins study area are plotted on trilinear diagrams **(Appendices G and H**). A trilinear diagram, also frequently referred to as a Piper diagram (Piper, 1944), provides a convenient method to classify and compare water types based on the ionic composition of different groundwater samples (Hem, 1985). Cation and anion concentrations for each groundwater sample are converted to total milliequivalents per liter (a milliequivalent is a measurement of the molar concentration of the ion, normalized by the ionic charge of the ion) and plotted as percentages of the respective totals into triangles (Appendices G and H). The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes a water type or hydrochemical facies (see Back, 1966).

5.7 Aquifer sensitivity and potential groundwater contaminant sources

Because groundwater is a resource only to the extent that it can be exploited for beneficial use to society, evaluation of potential threats of contamination of this resource is an important aspect of any assessment. It is axiomatic that protecting groundwater from contamination is much more rational than cleaning it up after it has been impacted through unsound practices.

In 1992 the Wyoming Department of Environmental Quality / Water Quality Division (WDEQ/WQD) in cooperation with the Wyoming Water Resources Center (WWRC) at the University of Wyoming, the Wyoming State Geological Survey (WSGS), the Wyoming Department of Agriculture (WDA), and the U.S. Environmental Protection Agency, Region VIII (EPA) initiated the Wyoming Ground Water Vulnerability Mapping Project to evaluate the vulnerability of the state's groundwater resources to contamination. This effort resulted in the publication of the *Wyoming Groundwater Vulnerability Assessment Handbook* by the Spatial Data and Visualization Center (SDVC) (Hamerlinck and Arneson, 1998). While the goal of the SDVC study was to develop a GIS-based tool to aid in planning, decision-making, and public education, the study developed GIS maps and associated digital databases that have been used for subsequent, related studies such as updates to the State Water Plan and this present Technical Memorandum. The aquifer sensitivity map and the GIS digital data used to develop it (average annual precipitation and recharge) are also used in this study to evaluate aquifer-specific recharge (Section 6.2.2). The methodology and purpose of the 1998 SDVC report and maps are discussed in this section.

Two map products from the SDVC study are used to help evaluate the potential for groundwater contamination in the WBRB: a map of average annual recharge (**Figure 5-2**) and a map of aquifer sensitivity (**Figure 5-3**). **Figures 5-4 through 5-10** are maps of potential groundwater contaminant sources in the WBRB that were prepared for this study to help identify areas of elevated potential contaminant risk. Specific sources of data used in developing **Figures 5-1 through 5-10** are included in **Appendix C**.

5.7.1 The Wyoming Groundwater Vulnerability Assessment Handbook and aquifer sensitivity

The Wyoming Ground Water Vulnerability Mapping Project was initiated to develop GIS-based mapping to assess the relative sensitivity and vulnerability of the state's groundwater resources to potential sources of contamination, primarily pesticides; to assist state and local agencies in identifying and prioritizing areas for groundwater monitoring; and to 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 shallowest groundwater, based solely on hydrogeologic characteristics. The SDVC definition is "aquifer sensitivity is a function of the intrinsic characteristics of the geologic material between ground surface and the saturated zone of an

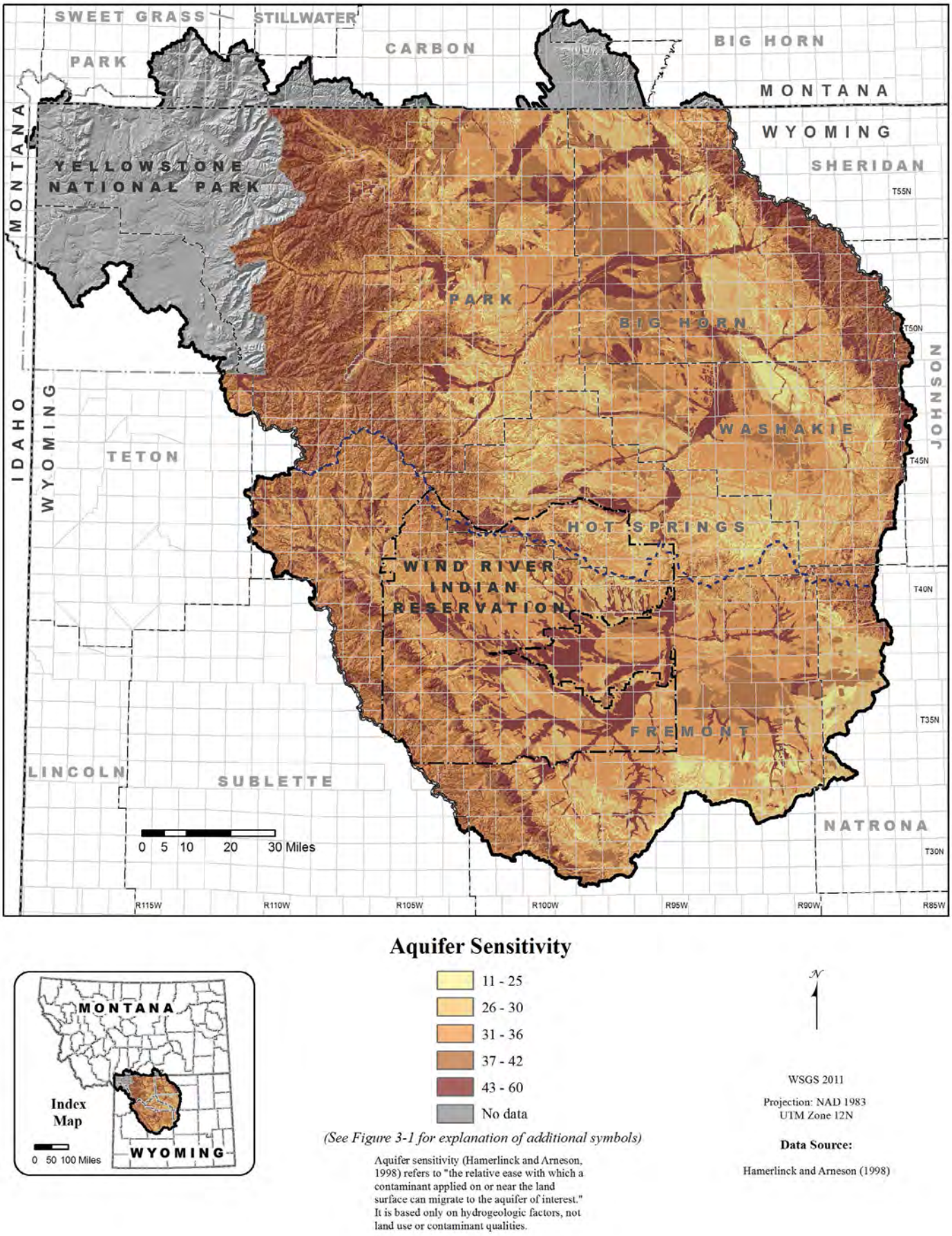


Figure 5-3. Aquifer sensitivity, Wyoming Wind/Bighorn River Basin.

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

The SDVC study assessed aquifer sensitivity using modified DRASTIC model methodology (U.S. Environmental Protection Agency, 1993) based on six independent parameters:

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

Aquifer sensitivity was assessed by rating each parameter, then summing the results to obtain sensitivity. The individual parameter ratings range from 1 to 10, based on how strongly a parameter affects aquifer sensitivity; a higher value indicates a greater effect. Aquifer sensitivity, therefore, ranges from 6 to 60.

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 with those of adjacent states or with other areas that have undergone similar studies. The sensitivity assessments are not appropriate for stand-alone site-specific application, and should be supplemented with additional investigations.
Figure 5-3 delineates five relative sensitivity categories for the WBRB that reflect the relative potential for contaminants to migrate from the ground surface to the uppermost groundwater (water table).

- The highest ranked areas **(43-60)** are located primarily over the main body of alluvial deposits within the basins, adjacent to rivers, streams, and lakes, and in the highly fractured mountainous belts that surround the basins. The high ranking in the alluvial areas is primarily the result of a combination of a generally shallow depth to groundwater within thicker alluvial aquifers, the high porosity of unconsolidated soils and weathered bedrock, and flat topography. The high rankings in mountainous areas result from heavily fractured bedrock, shallow groundwater within thin soil zones, and high rate of recharge.

- Medium-high ranked areas **(37-42)** are generally adjacent to and extend from the highest ranked areas, and are mostly located over alluvial materials or foothill zones. Groundwater in these areas is generally deeper and in thinner aquifers. Generally, more mature soils in these zones have more clay and loam content, and there is less fracturing in the bedrock exposed in the foothills than in more highly deformed mountainous areas.

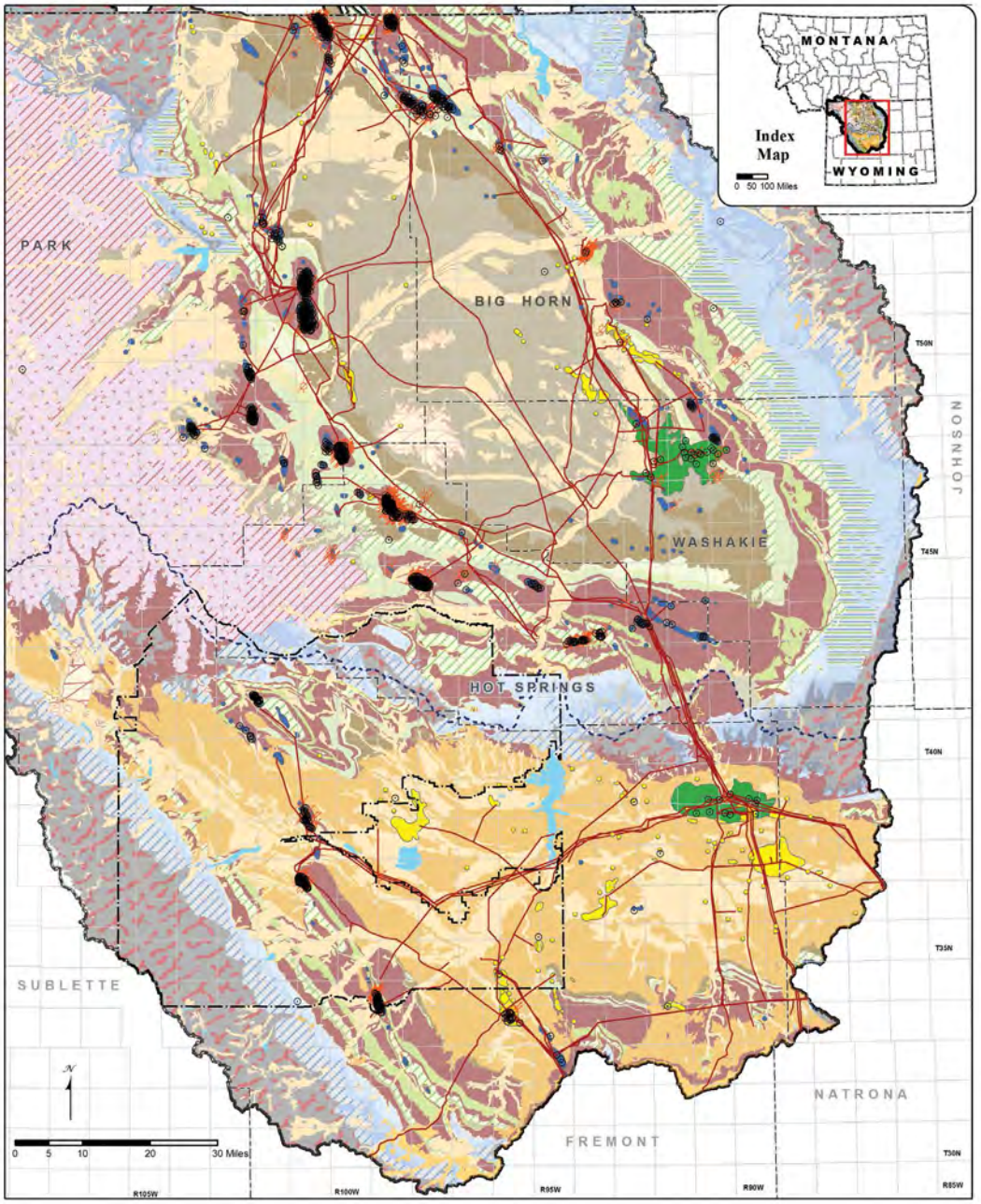
- Medium ranked areas **(31-36)** are prevalent in the remaining dry-land agricultural and grazing areas of the WBRB. These areas generally have relatively thicker, well-drained, mature soils, rolling topography with minor slope, and generally greater depth to the water table.

- Medium-low ranked areas **(26-30)** are generally characterized by low natural precipitation, low recharge, and deeper water tables. Generally, topography in these areas is rolling and bedrock is unfractured.

- Low ranked areas **(11-25)** have the deepest water tables and lower hydraulic conductivity in the vadose zone. Soils in these areas are generally poor for agriculture due to high clay content, very low average precipitation, or both.

5.7.2 Potential sources of groundwater contamination

Figures 5-4 through 5-10 map potential groundwater contaminant sources in the WBRB. Potential sources of groundwater contamination mapped for this study include facilities that deal with volumes of products, wastes, and other substances with physical and chemical characteristics that, released to the environment, could migrate to the water table. The mapped facilities pose a potential threat primarily



Explanation

(See Figure 3-1 for explanation of additional symbols)

- Hydrologic divide between the Wind and Bighorn river basins
- Wind River Reservation boundary

Potential Groundwater Contaminant Sources

- Active injector or disposal well
- Permanently abandoned injector or disposal well
- Pipeline
- Oil field
- Gas field
- Oil and gas field

Hydrogeologic Units
(for extended description, see Plate IV)

- Glacial ice
- Water
- Quaternary aquifers
- Undefined Tertiary units
- Tertiary aquifers
- Undefined Mesozoic aquifers
- Mesozoic aquifers
- Undifferentiated Mesozoic and Paleozoic units
- Undefined Paleozoic units
- Paleozoic aquifers
- Precambrian
- Undefined volcanics
- Absaroka-Yellowstone volcanics
- Confining units

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:
Wyoming Oil and Gas Conservation Commission
Wyoming State Geological Survey
Wyoming Pipeline Authority

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

to unconfined water-table aquifers and to commonly confined aquifers in their outcrop/recharge areas (where they are unconfined). **Figure 5-3** shows areas where migration to the water table is most likely.

The identification and mapping of facilities as potential sources of groundwater contamination ***does not*** imply that those facilities are impacting groundwater (except specific facilities where contamination has been confirmed). Generally, the facilities identified as potential contaminant sources in Wyoming are strictly regulated by a government agency or agencies to prevent contaminant releases and protect groundwater resources, human health, and the environment.

In order to develop as comprehensive a summary as practical of the various potential sources of groundwater contamination in the WBRB, the following list of facility types and the agencies with jurisdiction over their permitting, operations, and inventory was compiled:

WDEQ Water Quality Division:

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

WDEQ Solid and Hazardous Waste Division:

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

WDEQ Land Quality and Abandoned Mine Land Divisions:

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

Wyoming Oil & Gas Conservation Commission:

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

Wyoming State Geological Survey:

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

The agencies were contacted to obtain available data suitable for mapping the various potential contaminant sources. Location data for similar potential contaminant sources were grouped for presentation on an abridged version of the surface hydrogeology map (**Plate IV**): the groupings in **Figures 5-4 through 5-10** are generally not by agency, but rather by similarity of facilities (and presentation considerations such as density of data points).

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

- **Oil and gas fields**: Oil and gas exploration, production, processing, and transportation facilities, in addition to handling large volumes of petroleum hydrocarbons and produced water, typically also handle substantial volumes of products that can pose a threat to groundwater such as fuel, methanol, glycols, amines, lubrication and hydraulic oils, acids, and a variety of well fracing and treatment chemicals. Large volumes of waste and wastewater are typically generated by oil and gas operations. Releases can occur from storage tanks, process vessels, and above-ground and underground piping. In some cases hydrocarbons, produced water, and other chemicals are discharged to pits. Older and abandoned pits, commonly unlined, have greater potential for groundwater contamination. Notably, the historic storage and disposal of relatively mobile natural gas condensate in unlined pits has resulted in confirmed shallow groundwater contamination at several locations in the WBRB. Contamination of groundwater by the release of petroleum hydrocarbons is a primary concern of local, state, and federal agencies.

- **Pipelines**: Interstate and intrastate pipelines transport a variety of liquids that if released by rupture, malfunction, operational problems, or leaks can migrate to groundwater. Small leaks from buried pipelines can go undetected for long periods and cause substantial releases.

- **Active and permanently abandoned injector and disposal wells**: Wells permitted by the WOGCC for produced water disposal by injection into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources – for maintaining

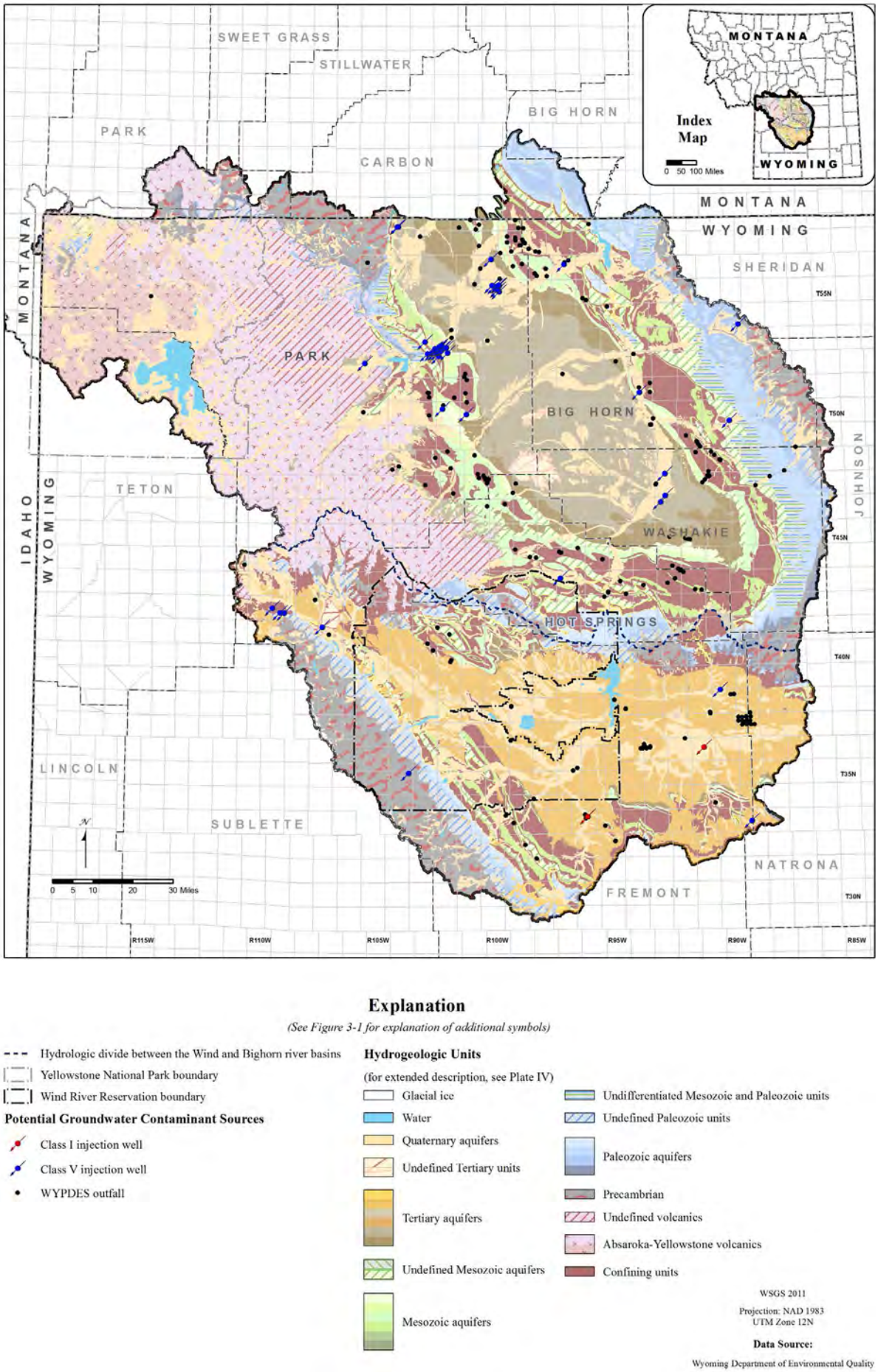


Figure 5-5. Potential groundwater contaminant sources: Class I and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program and active outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program, Wyoming Wind/Bighorn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

reservoir pressure for enhanced oil recovery and other purposes – are mapped because there are many of them in the WBRB and because they typically receive large volumes of produced water that would be a pollutant if leaked into shallow aquifers containing useable groundwater. Injection facilities also generally include bulk storage (tanks), piping, and other equipment that could release produced water or other potential contaminants in recharge areas. In general, Class II wells are strictly regulated by WOGCC; and except for excursions through injector-well casing, there is minimal potential for impacting groundwater resources. Class II injection wells are located within oil and gas fields.

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

- **Class I UIC injection wells**: Class I underground injection wells and Class V injection facilities are permitted through the WDEQ Underground Injection Control (UIC) Program. In Wyoming, Class I wells inject non-hazardous wastes (RCRA definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal makes up a large component of injected fluids; and, like Class II wells, Class I wells are strictly regulated and generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes that they are allowed to accept for injection. In contrast, Class V facilities are used to inject a wide range of non-hazardous fluids generally above or directly into shallow aquifers and therefore have a substantial capacity for impacting groundwater resources. Many Class V wells in Wyoming are associated with groundwater contamination, and new injection of industrial wastes has been banned. Notable examples of Class V facilities are agricultural or storm water drainage wells, large-capacity septic systems, automotive and industrial waste disposal wells, and various types of infiltration galleries. Class I and Class V injection facilities also generally include bulk storage (tanks) that could release contaminants in recharge areas.

- **Active WYPDES outfalls**: Discharge of any pollutant from a point source into surface waters of the state requires a WDEQ Wyoming Pollutant Discharge Elimination System (WYPDES) permit from the Water Quality Division (WQD). During flow to surface waters (where contaminants may be diluted), discharged water may flow through dry drainages; and to the extent that the discharge could recharge shallow groundwater, it is a potential source of contamination. Pits and other impoundments, spreader dikes, etc. are commonly installed along WYPDES flow paths to slow flow rates and remove sediment, enhancing the amount that can infiltrate to the subsurface. WYPDES outfalls are associated with a variety of facilities in the WBRB; many discharge produced water from oil and gas operations.

Figure 5-6 – Potential groundwater contaminant sources – WDEQ solid and hazardous waste facilities and CAFOs, WBRB

- **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
  - solid waste treatment, storage, and disposal facilities
  - spill and hazardous waste corrective action sites
  - illegal dump sites and historic site cleanups

Solid and hazardous waste facilities can contain a wide variety of potential contaminants in a variety of configurations. Wastes may be liquid, solid or semisolid, above or below ground, contained, or uncontained. Wastes are generally concentrated at these facilities. Below-ground waste can intersect shallow groundwater, and infiltration of water from precipitation and other sources can develop a leachate composed of many contaminants as it infiltrates wastes and contaminated soil above the water table. Active facilities may also store bulk products on-site (e.g., fuel) that can be a source of contamination if released.

- **CAFOs**: Concentrated animal feeding operations are permitted by the SHWD. Outfalls from CAFOs are also permitted under the WYPDES Program. The primary potential contaminant generated at CAFOs is animal waste. Other farm and ranch potential contaminant sources include stored bulk products (fuels, antifreeze, used oil, pesticides, herbicides), "ranch dumps," and landfills.

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

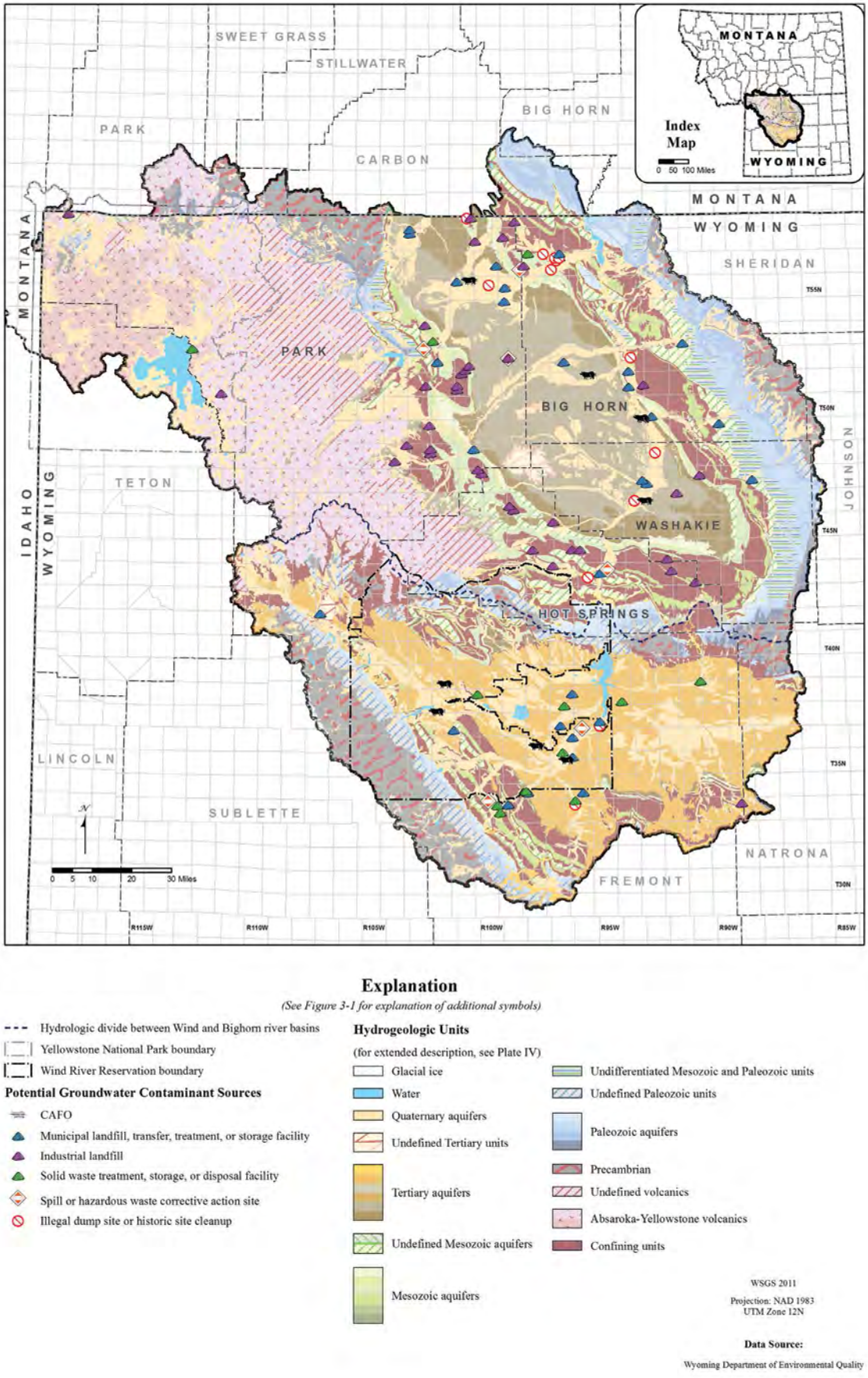


Figure 5-6. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality permitted and inventoried solid and hazardous waste facilities, and concentrated animal feeding operations (CAFOs), Wyoming Wind/Bighorn River Basin.

- **Active storage tanks**: In use or temporarily out of use, aboveground 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 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 underground storage tanks.

- **VRP and ICP sites**: These are sites where soil or groundwater contamination is remediated by agreement between the SHWD and the responsible party under the Voluntary Remediation Program (VRP). By definition, sites enrolled in this program are associated with contaminated soil or groundwater or both.

- **Orphan and brownfield assistance sites**: These are contaminated sites where a viable responsible party other than the state does not exist (orphans), or sites with known or suspected contamination that are owned by local governments (brownfields).

- **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 a variety of wastes with prior approval of the WDEQ. Produced water disposed of at these facilities is commonly accompanied by liquid hydrocarbons, which are generally recovered for sale. Releases can occur from malfunctions, operational problems, and above-ground and underground leaks directly from the pits.

- **Known contaminated areas**: These sites are generally regulated by the WQD Groundwater Pollution Control Program. They include sites with confirmed soil and groundwater contamination that have not entered the VRP and are being addressed under orders from the WDEQ.

Figures 5-7 through 5-9 show the locations of a variety of active and abandoned mines, quarries, pits, and similar operations. These facilities and sites can impact groundwater in several similar ways. Stripping soil from an area increases infiltration and removes the capacity for biodegradation and retardation of contaminants within the soil horizon. Excavations can impound water, some in large quantities, that can enhance recharge to groundwater or become hydraulically connected to the water table along with contaminants. Exposure of metal-rich lithologies to the atmosphere can oxidize and mobilize dissolved concentrations. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) and wastes stored or generated can more quickly infiltrate to the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-8 – Potential groundwater contaminant sources – WDEQ Land Quality Division (LQD) permitted mines, WBRB includes three active mine types regulated by the WDEQ Land Quality Division (LQD) and active coal mines mapped by the WSGS.

- **Active limited mining operations (LMOs)** are exempt from the DEQ's full permitting process. LMOs are restricted to a maximum of 10 acres for the life of the mine.
- **Active small mines** do not have a limit on total disturbance area, but may only disturb up to 10 acres per year.
- **Active large mines** have no limit on total disturbance area or on how many acres may be disturbed per year.
- **Active coal mines** mapped by the WSGS are also included in **Figure 5-7**.

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

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

5.7.3 Discussion

Available location information that could be compiled in ARC/GIS format was necessary for a potential contaminant source to be included in this study. Some of the types of facilities listed below do not exist in the WBRB. Some of the contaminant source types do not currently have the location information required for mapping, or the data exist but were not available. The following types of potential groundwater contaminant sources were not mapped in this study:

- Class III wells are used to inject fluids for in-situ solution mining of various minerals (e.g., uranium). Although Class III injection wells exist in the WBRB,

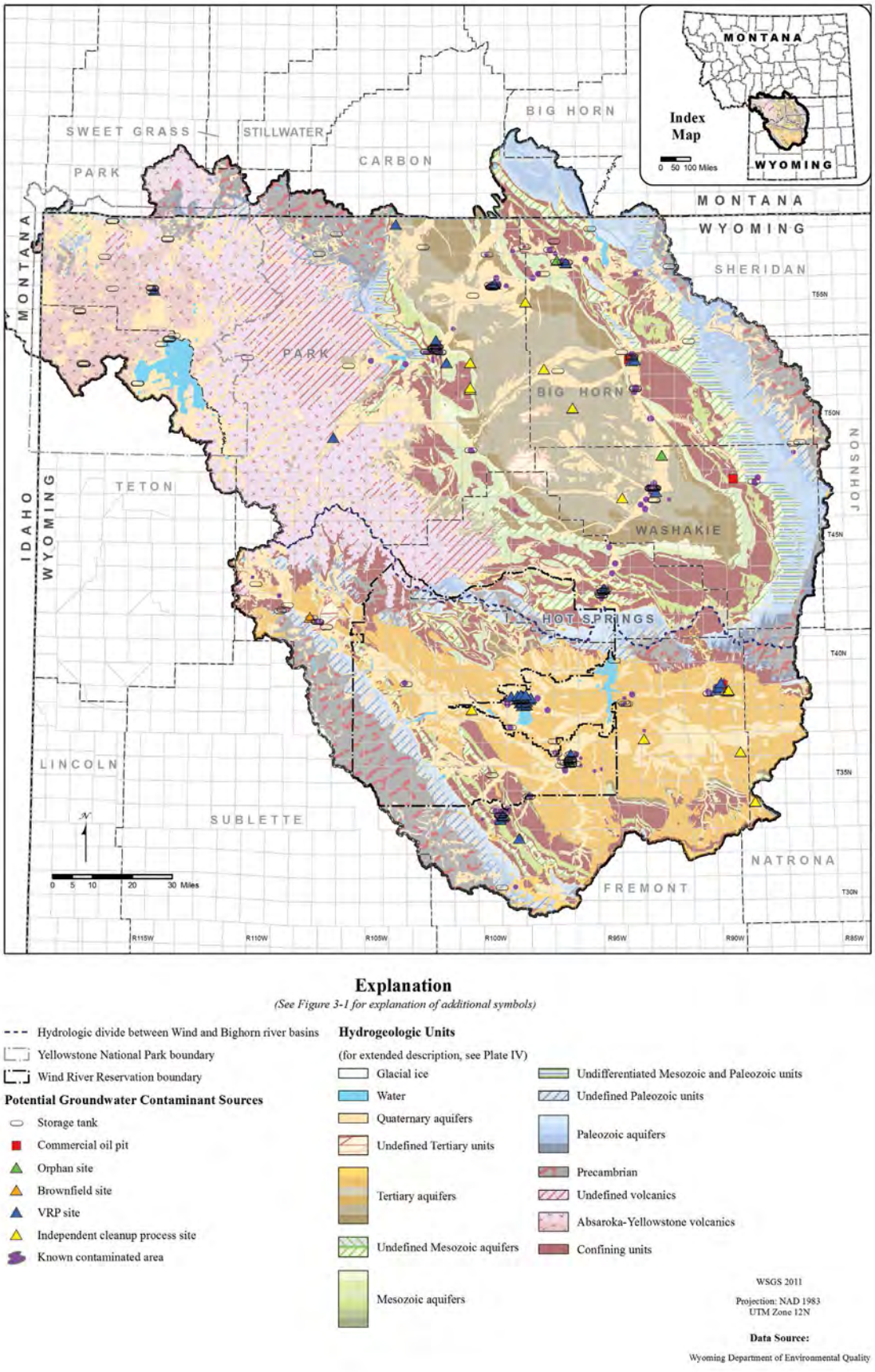


Figure 5-7. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality (WDEQ) permitted storage tanks and commercial disposal pits; WDEQ Voluntary Remediation Program (VRP), Brownfield, Independent cleanup process (ICP), and orphan sites; and known contaminated areas in WDEQ's groundwater program, Wyoming Wind/Bighorn River Basin.

data were not available.

- Although a large number of public owned treatment works (POTWs) and septic systems exist in the WBRB, they were not mapped because adequate location data were not available. Some large-capacity septic systems were mapped as Class V injection facilities (**Figure 5-5**).

- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of major irrigation districts presented in the Wind-Bighorn Basin Plan Update (MWH et al., 2010, Figure 23) shows the primary areas where agricultural chemicals would generally be applied in the WBRB. In addition, the recent USGS report, Occurrence of Pesticides in Groundwater of Wyoming, 1995-2006 (Bartos et al., 2009) presents the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC (Hamerlinck and Arneson, 1998) report to be most vulnerable to this type of contamination. The application of pesticides and herbicides is regulated by the WDEQ Nonpoint Source Program.

- There are currently no underground coal gassification (UGC) sites in the WBRB.

- Produced water pits regulated by the WOGCC were not individually mapped for this study. These potential sources are located within the oil and gas fields mapped in **Figure 5-4**.

- Oil and gas field plants and compressor stations are likewise located within the oil and gas fields mapped in **Figure 5-4**.

- Construction/demolition landfills, hazardous waste and used oil generators, used oil transporter and storage facilities, one-time disposal authorizations, mobile treatment units, de minimus spills, and complaints were included in the data received from the Solid and Hazardous Waste Division but are not shown on **Figure 5-6** due to variable location (mobile) or relatively low potential for contaminating groundwater.

The list and description above of potential groundwater contaminant sources may well be incomplete. There may be additional potential sources associated with products and wastes in sufficient volume to be of concern that were overlooked in this study. With 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 at a later date in the on-line presentation of this study or in the next update of this memorandum.

5.7.3.1 Source Water Assessment Program and Wyoming Statewide Groundwater Protection Strategy

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) and other public systems (rest areas, parks, etc.), is an additional source of information on local area potential 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) for groundwater PWSs. Source-water assessments include determining the source-water contributing area, inventorying of potential sources of contamination for each PWS, determining the susceptibility of the PWS to identified potential contaminants, and summarizing the information in a report. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming. Additional information on the SWAP in Wyoming can be accessed at:

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

Copies of the Source Water Assessment Reports for specific PWSs in the WBRB can be accessed at:

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

A DRAFT Wyoming Statewide Groundwater Protection Strategy: Phase I – Aquifer Prioritization report is currently being prepared by cooperating agencies. The overall Strategy is to develop an ambient groundwater quality database and a monitoring and assessment plan 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
- Phase II – Groundwater monitoring plan design
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

The first "prioritization of Wyoming aquifers for the purpose of ambient groundwater monitoring" is to ensure that resources are applied to assessing aquifers (primarily those used as sources of drinking water) that are most susceptible to contamination. This information will be summarized in

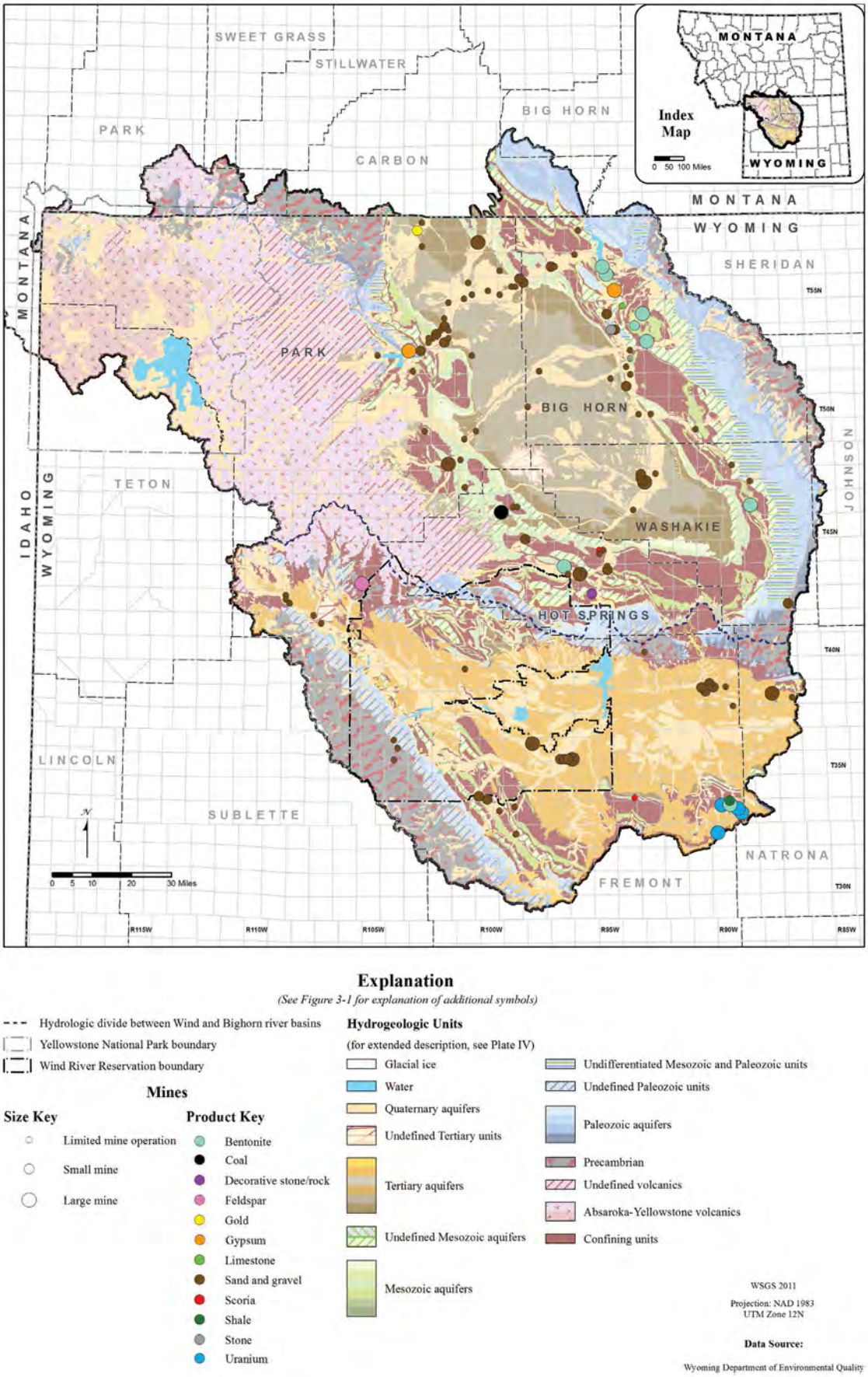


Figure 5-8. Potential Groundwater Contaminant Sources: Wyoming Department of Environmental Quality Land Quality Division permitted mines, {quarries, and pits}, Wyoming Wind/Bighorn River Basin.

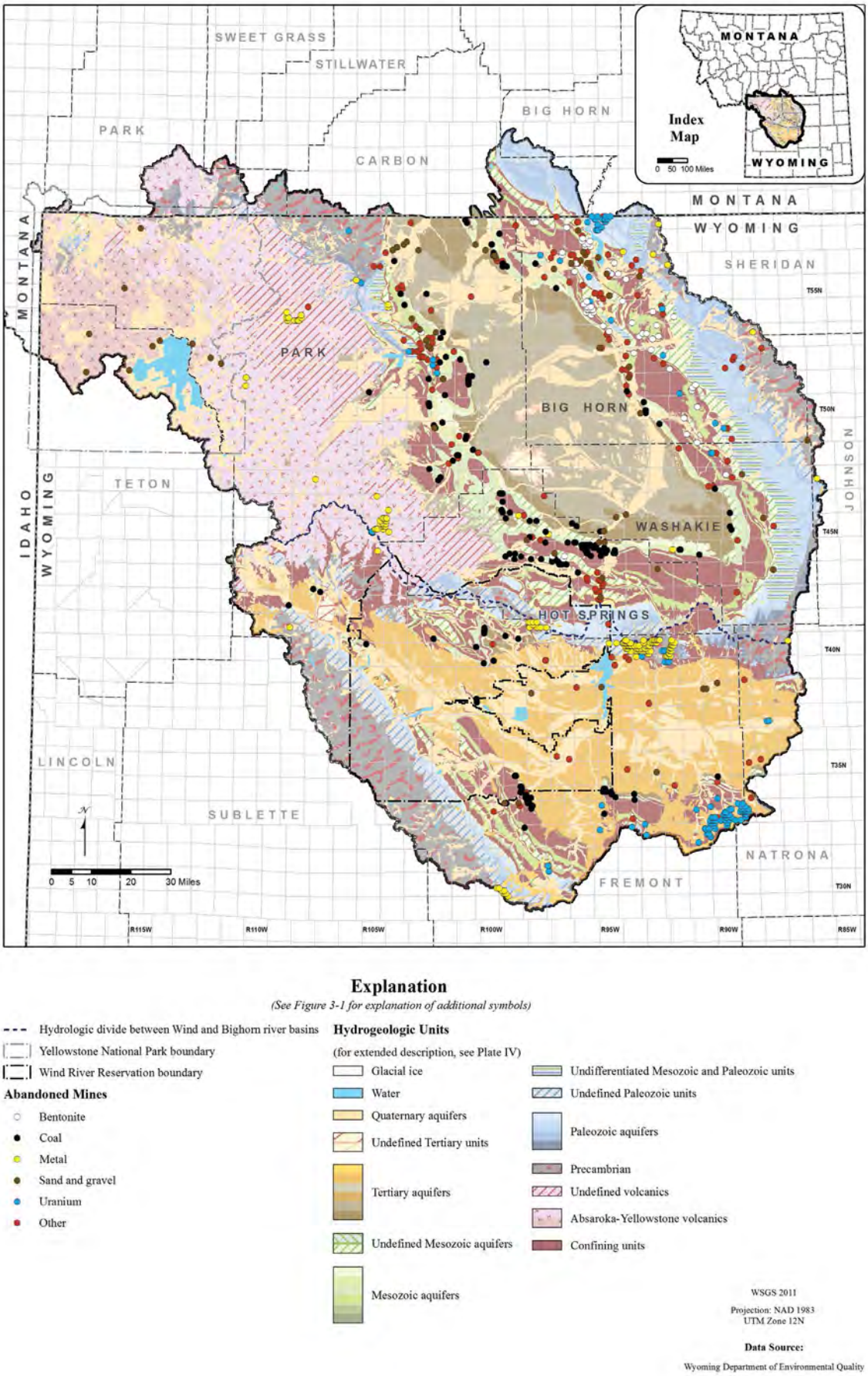


Figure 5-9. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality Abandoned Mine Land Divsion abandoned mine sites, Wyoming Wind/Bighorn River Basin.

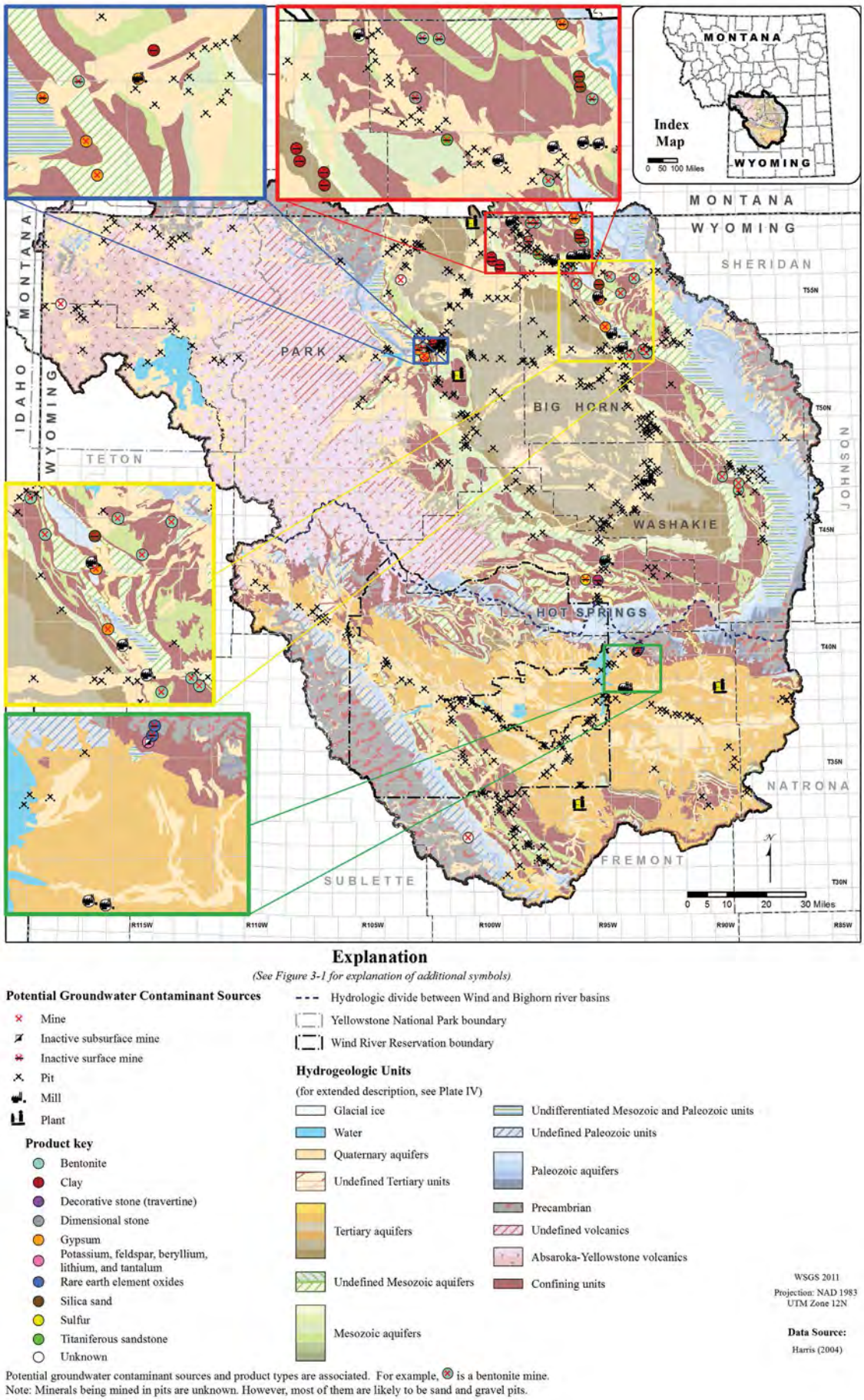


Figure 5-10. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Wyoming Wind/Bighorn River Basin, (locations from Harris, 2004).

the Draft Phase I Report. The Phase I report builds on the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) determination of the relative sensitivity of shallow groundwater to contamination. The Phase I report identifies areas and aquifers that should be included in the statewide ambient groundwater monitoring plan, and includes a map of "Aquifer Prioritization for Ambient Groundwater Monitoring" developed by combining the aquifer sensitivity map of Hamerlinck and Arneson with maps prepared for the plan, including maps of

- 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
- Land use: rural residential development
- Land use: oil and gas exploration, development, and pipelines
- Land use: known and potential contaminant sources
- Land use: croplands and urban areas
- Land use: mining
- Composite land use (up to six uses)

On the basis of aquifer sensitivity, current water use, and current land use, the Aquifer Prioritization map distinguishes four relative priority categories within high-use aquifer/areas (Low, Low-Moderate, Moderate-High, and High). The Phase I report discusses how the high-use aquifers in Wyoming were prioritized and discusses the High-priority aquifers in detail. The Phase I report also describes the existing data and the ongoing sources of groundwater quality data that could be organized and included in the plan.

Section 5.7 of this memorandum addresses the common goal of The Wyoming Statewide Groundwater Protection Strategy and the SWAP/WHP to inventory potential sources of groundwater resource contamination. All three programs can benefit by considering the focus of the others and including relevant information, either directly or by reference, to supplement their databases. Organizing as much groundwater quality (and hydrology) information as practicable into an evolving master database, as addressed in the Strategy, would be very useful in protecting and sustainably developing the groundwater resources of the WBRB and throughout Wyoming.

5.8 Glossary

- *Artesian conditions* – occur where the potentiometric surface of a confined aquifer is at a higher elevation than the top of the aquifer. Water in wells at these locations will rise above the top of the aquifer to the level of the potentiometric surface.
- *Capillarity* – the effect of surface tension and molecular attraction between liquids and solids that causes water within the vadose zone (above the water table) to be at less than atmospheric pressure. Groundwater in the *capillary fringe* immediately above the *water table* will be subject to an upward attraction.
- *Discharge* – groundwater that flows from an aquifer. Discharge from an aquifer can occur naturally by flow into streams or lakes, by leakage into adjacent geologic units, by flow from springs, by near-surface evapotranspiration, or artificially by pumping from wells.
- *Drawdown* – the lowering of the groundwater (potentiometric) surface (*head*) by discharge from an aquifer (pumping or natural discharge) expressed in feet of water-level change. A rise in groundwater level is the opposite of drawdown.
- *Effective porosity* – the proportion of the *porosity* in a volume of earth material that is interconnected and allows flow of groundwater. Water attached to solid surfaces within the total interconnected total porosity decreases effective porosity. Effective *porosity* is always less than porosity.
- *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).
- *Gaining stream* – a surface water stream, or part of a stream, which receives groundwater discharged from underlying or adjacent hydrogeologic unit(s). Surface water flow attributed to groundwater is commonly referred to as *base flow*.
- *Geochemical water type* – an expression of the dominant cations and anions dissolved in groundwater.
- *Hydraulic conductivity* – a measure of the capacity of earth materials to transmit groundwater, expressed as the amount of water that can flow through the interconnected open spaces in earth materials in terms of velocity (ft/day) or gallons per day per square foot (gpd/ft^2). *Hydraulic conductivity* is dependent on the characteristics of both the porous earth material and the fluid, and can be as variable as the lithologies that compose the earth's crust. It can vary by direction, commonly much higher parallel to stratification than across it.
- *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.

- *Losing stream* – a surface-water stream or part of a stream that recharges the underlying or adjacent hydrogeologic unit(s), which results in decreased flow in the stream.
- *Permeability* – differs from *hydraulic conductivity* in that it depends only on the characteristics of the porous material. The dimensions of permeability are Length^2 (ft^2, cm^2, m^2, etc.). *Permeability* is the parameter preferred by the oil and gas industry: it is more practical for evaluating multi-phase (oil, gas, water) fluid flow.
- *Porosity* (total) – the proportion of void or open-space volume (intergranular space, fractures, solution cavities, etc.) in a total volume of earth material (soil, unconsolidated deposit, bedrock), expressed as a percentage or decimal fraction.
- *Recharge* – water that infiltrates at ground surface, penetrates the vadose zone, and reaches the *water table*.
- *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 retention* – the ratio of the volume of water retained in the pores of an unconfined aquifer after gravity drainage to the volume of previously saturated earth material.
- *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 how much water is available for beneficial use. Compare *specific yield* to *porosity* and *effective porosity*. Both are dimensionless, but used in the same equation (multiplied by saturated volume) porosity will return total groundwater volume while specific yield will return available groundwater volume (Sections 5.1.4 and 6.2.1).
- *Static head or static water level* – the level of water in a well when the well and surrounding wells are not being pumped and the *total head* in the aquifer is generally (over a short time-frame) at equilibrium. *Static head* or water level is commonly expressed in feet of elevation above mean sea level (ft-msl).
- *Storage* (total) – the total volume of groundwater contained within a volume of earth material – equal to saturated volume times porosity. *Storage* changes in response to changes in recharge and discharge.
- *Storage coefficient* – the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head. Like *specific yield*, because dimensions in the numerator and denominator cancel, *storage coefficient* is a dimensionless parameter. In an unconfined aquifer, water released from storage is from gravity drainage and *storage coefficient* is essentially equivalent to *specific yield*. In a confined aquifer, water released from storage (*specific storage*) is primarily from expansion of the water and compression of the aquifer. 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}).
- *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).
- *Total head* – the height of a column of water above a datum due to a combination of elevation head and pressure head.
- *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 gallons per day per foot (gpd/ft). *Transmissivity* is equivalent to the hydraulic conductivity integrated over the thickness of an aquifer.
- *Vadose zone* – the unsaturated soil and weathered bedrock interval between ground surface and the *water table*.
- *Well yield* – the rate of groundwater discharged (pumped or flowing) from a well, expressed in gallons per minute (gpm).

Chapter 6

WBRB Hydrogeology and Groundwater Resources

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Brett Worman
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Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. The hydrogeologic units in the WBRB are variably permeable (aquifers) or impermeable (confining units) to the flow of groundwater. The heterogeneity at all scales in geologic or hydrogeologic units confounds their classification as aquifers or confining units. **Figure 6-1** shows the great lithologic and grain-size heterogeneity measured in several typical hydrogeologic units in the Elk Basin (Bighorn Basin), and indicates how it is that virtually any geologic unit in the basin may yield at least small quantities of groundwater to wells. Even wells completed within a confining unit may produce water if the unit is saturated. For example, although the Cody Shale and Thermopolis Shale are classified as confining units, several domestic supply and stock wells have been completed in these units, according to records of the Wyoming State Engineer's Office.

This study covers the WBRB specifically; the conceptual models presented for WBRB recharge, discharge, storage, and flow may be applied generally to the major drainage basins in Wyoming. However, data on aquifer recharge, groundwater flow, aquifer discharge, subsurface inter-aquifer mixing, and total groundwater quantities available in the WBRB (and the other Wyoming basins) are sparse relative to the large area and stratigraphic and structural complexity of the basins. This sparsity of data precludes an accurate site-specific groundwater model for the WBRB. Computer or conceptual modeling of the stratigraphy, structure, groundwater flow, and water quality, quantity, and availability should allow for periodic updating and increasing reliability as data continue to be collected.

For the upper 1,000 feet of the *interior basin areas* of the Wind River and Bighorn River basins, the total amount of stored groundwater and the amount of available (producible) groundwater are estimated in this chapter. The stored and available groundwater in Quaternary unconsolidated deposits in the WBRB are also estimated. And, recharge to hydrogeologic units and groupings of hydrogeologic units is estimated using annual recharge mapped over the outcrop areas that together cover the basin.

6.1 Hydrostratigraphy

Several previous regional studies in the Wind River and Bighorn basins (Section 2.1) have grouped the geologic units into aquifers and aquifer systems to facilitate the regional description and assessment of the basins' groundwater resources. The hydrostratigraphy of the WBRB developed for this study, based on the previous regional assessments, is shown on **Plates II, III,** and **IV**. **Plates II** and **III** summarize the hydrogeologic nomenclature used in this study, nomenclature from previous studies, and the aquifer classification system in the Statewide Framework Water Plan (WWC Engineering, 2007) for the Wind River and Bighorn Basins, respectively. **Plate IV** is a surface hydrogeologic map of the entire WBRB. **Appendix A** provides detailed descriptions of the WBRB geologic units in Wyoming and Montana that were compiled for the surface hydrogeology shown on **Plate IV**.

6.1.1 Wind River Basin hydrostratigraphy (updated from Richter, 1981)

The Wind River Basin hydrogeologic units defined for this study are described below, youngest to oldest (**Plate II**, far right column). Bracketed […] classifications below are from the Statewide Framework Water Plan (WWC Engineering, 2007). Below the major alluvial aquifer at the land surface and above the thick, widespread Upper Cretaceous Cody major confining unit are three Tertiary or Upper Cretaceous major sandstone aquifers (Split Rock, White River, Lance) and two major confining units (Indian Meadows, Meeteetse-Lewis); the aquifers are generally accessible in the central basins. Below the Cody confining unit and above the Precambrian basal major confining unit, lower Mesozoic and Paleozoic hydrogeologic units include one major sandstone aquifer (nugget) and five major limestone aquifers (Tensleep, Madison, Darby, Bighorn, Flathead); these aquifers are generally accessible in and near outcrop along the basin margins.

Where present with sufficient thickness, ***Quaternary unconsolidated deposit aquifers*** – alluvium and terrace, landslide, eolian, and glacial deposits – constitute important [Major] aquifers in the basin. Upper Tertiary bedrock aquifers crop out only along the southernmost margin of the Wind River Basin. Lower Tertiary and Upper Cretaceous aquifers are lenticular, discontinuous sandstone bodies that are hydraulically isolated to varying degrees by interbedded fine-grained confining units. The Tertiary and Upper Cretaceous hydrogeologic units above the ***Cody*** *[Major]* ***confining unit*** include, youngest to oldest:

- the Split Rock [Major Sandstone] aquifer
- the White River [Marginal] aquifer
- the Aycross–Wagon Bed confining unit [Marginal aquifer]
- the Wind River [Major Sandstone] aquifer
- the Indian Meadows [Major] confining unit
- the Fort Union–Lance aquifer, including:
    - the Fort Union [Minor] aquifer
    - the Lance [Major Sandstone] aquifer
- the Meeteetse–Lewis [Major] confining unit
- the Mesaverde [Minor] aquifer, including:
    - the Teapot [Minor] Sandstone aquifer
    - the Middle confining unit
    - the Parkman [Minor] Sandstone aquifer
    - a confining unit (Wallace Creek tongue of the Cody Shale)
    - the Fales [Minor] Sandstone aquifer

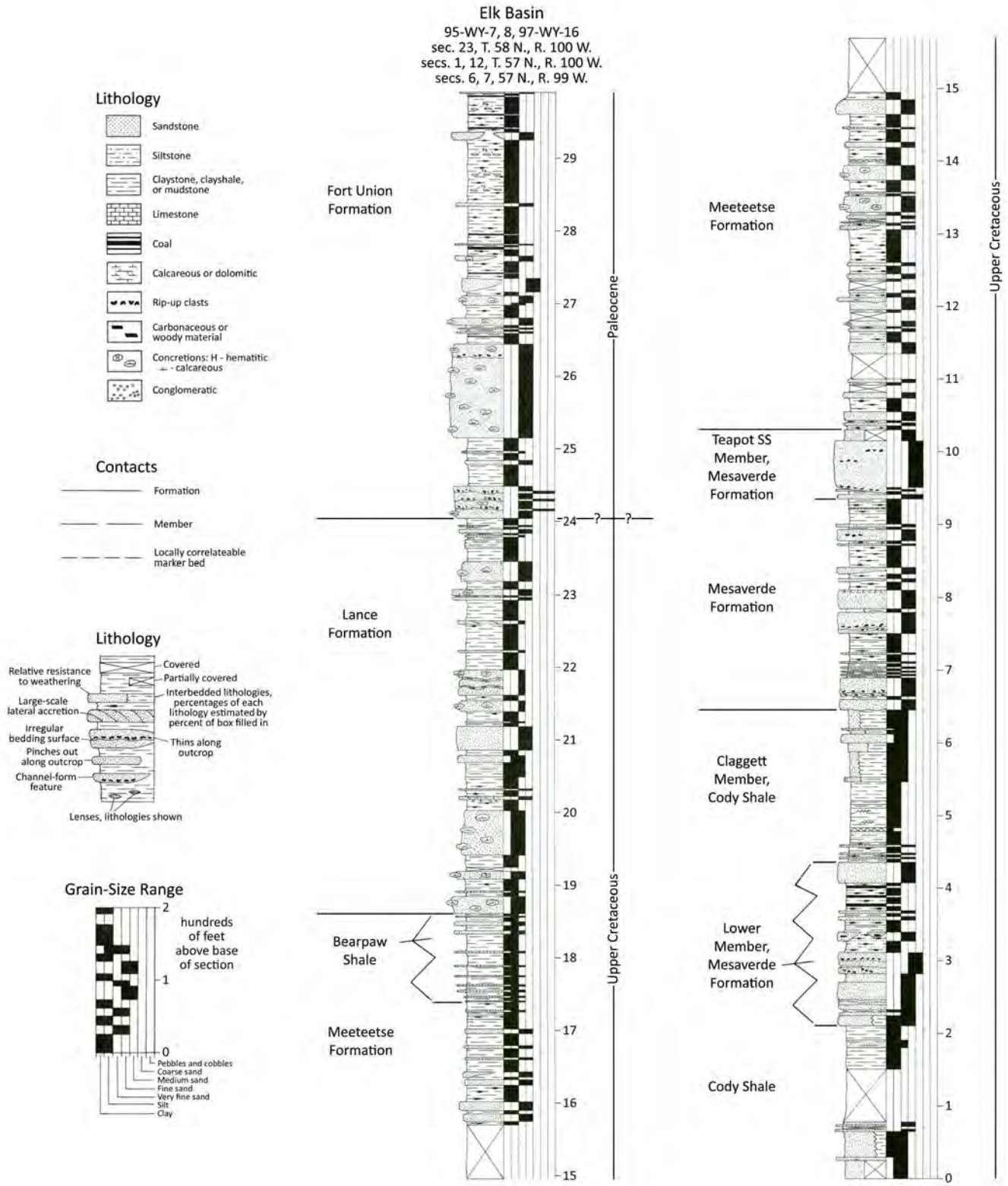


Figure 6-1. Detailed composite measured section of the lower Fort Union, Lance, Meeteetse, and Mesaverde Formations and upper Cody Shale, Elk Basin (Bighorn Basin), Wyoming, showing lithology and grain-size distribution. Modified from Johnson, Keefer, Keighin, and Finn, 1998, Plates I and II.

Immediately below the ***Cody*** *[Major]* ***confining unit***, the ***lower and middle Mesozoic aquifers and confining units*** aquifer system is composed of [Major], [Minor], and [Marginal] aquifers and confining units dominated by sandstone, siltstone, and shale lithologies. While some of the aquifers are lenticular and discontinuous, they are generally more continuous and laterally extensive than the lower Tertiary and Upper Cretaceous aquifers above the Cody Shale. The ***lower and middle Mesozoic aquifers and confining units*** include substantial confining units that hydraulically isolate some component aquifers of the system. The ***lower and middle Mesozoic aquifers and confining units*** aquifer system includes, youngest to oldest:

- the Frontier [Minor] aquifer, including:
  - a basal confining unit
- the Mowry–Thermopolis [Major] confining unit, including:
  - the Mowry [Major] confining unit
  - the Muddy Sandstone aquifer (locally interbedded within the Mowry and Thermopolis shales)
  - the Thermopolis [Major] confining unit
- the Cloverly [Minor] aquifer
- the Morrison confining unit [Minor aquifer]
- the Sundance–Nugget aquifer, including:
  - the Sundance [Minor] aquifer
  - the Gypsum Spring confining unit [Marginal aquifer]
  - the Nugget Sandstone [Major Sandstone] aquifer
- the Chugwater–Dinwoody [Marginal] aquifer and confining unit, including:
  - the Chugwater [Marginal] aquifer, including:
    - the Popo Agie confining unit
    - the Crow Mountain [Marginal] aquifer
    - the Alcova confining unit
    - the Red Peak [Marginal] aquifer
  - the Dinwoody confining unit [Marginal aquifer]

Although included here in the ***lower and middle Mesozoic aquifers and confining units*** **(Plate II)**, the Dinwoody Formation is variously considered the uppermost unit of the underlying Goose Egg-Phosphoria aquifer and confining unit. The mostly Permian ***Goose Egg–Phosphoria*** *[Minor]* ***aquifer and confining unit*** separates the Lower and middle Mesozoic aquifers and confining units system from the Paleozoic aquifer system.

The ***Paleozoic aquifer system*** includes Pennsylvanian through Ordovician carbonate aquifers that are well known for producing high volumes of groundwater at and near the flanks of the Laramide uplifts surrounding the basins where permeability has been structurally enhanced by solution-enlarged fractures. The component ***Paleozoic aquifer system*** hydrogeologic units are, youngest to oldest:

- the Tensleep [Major Limestone] aquifer
- the Amsden [Marginal] aquifer
- the Madison [Major Limestone] aquifer
- the Darby [Major Limestone] aquifer
- the Bighorn [Major Limestone or Minor] aquifer

The ***Paleozoic aquifer system*** is underlain by the Cambrian ***Gallatin–Gros Ventre confining unit***, the Cambrian ***Flathead aquifer***, and the ***Precambrian basal confining unit,*** described as follows:

- the Gallatin–Gros Ventre confining unit, including:
  - the Gallatin confining unit [Minor aquifer]
  - the Gros Ventre confining unit [Minor aquifer]
- the Flathead [Major Limestone] aquifer
- the Precambrian basal [Major] confining unit

The Precambrian basement complex is a marginal aquifer locally where it is exposed and fractured in the cores of the Laramide uplifts, where thin and disconnected soil, deeply weathered bedrock, and shallow fractures provide transmissive zones. Where these conditions do not exist at land surface, and virtually everywhere in the subsurface, the Precambrian basement is the basal confining unit for the structural groundwater basins in the WBRB and throughout Wyoming.

6.1.2 Bighorn Basin hydrostratigraphy (updated from Libra et al., 1981)

The Bighorn Basin hydrogeologic units defined for this study are described below, youngest to oldest (**Plate III**, far right column). Bracketed […] classifications are from the Statewide Framework Water Plan (WWC Engineering, 2007). Below the major alluvial aquifer at the land surface and above the thick, widespread Upper Cretaceous ***Cody*** *[Major]* ***confining unit*** are three Tertiary or Upper Cretaceous major (mostly sandstone) aquifers (Fort Union, Lance, Mesaverde) and one major confining unit (Meeteetse), all components of the ***lower Tertiary/Upper Cretaceous aquifer system***; the aquifers are generally accessible in the central basins. Below the ***Cody confining unit*** and above the ***Precambrian basal*** *[Major]* ***confining unit***, lower Mesozoic and Paleozoic hydrogeologic units include two major sandstone aquifers (Cloverly, Nugget), five major limestone aquifers (Tensleep, Madison, Darby, Bighorn, Flathead) and two major confining units (Mowry, Thermopolis); the aquifers are generally accessible in and near outcrop along the basin margins.

Where present with sufficient thickness, unconsolidated ***Quaternary alluvial aquifers and terrace deposits*** constitute

important [Major] aquifers within the basin. The Upper Tertiary bedrock hydrostratigraphy of the Bighorn Basin includes the Oligocene ***White River*** *[Marginal]* ***aquifer*** and the upper Eocene ***Wagon Bed confining unit*** *[Marginal aquifer]*. The Tertiary Absaroka Volcanics represent a largely undeveloped groundwater resource; development is impeded by complex to chaotic stratigraphy within the deeply eroded, high-relief, and mostly inaccessible Absaroka Range.

Below the Wagon Bed, three hydrogeologic systems (each composed of several hydrogeologic units) separated by two regional confining units compose the hydrogeology of the Bighorn Basin. Hydrologic interconnection between units within the aquifer systems varies due to the presence or absence of local confining units and fracture zones. Likewise, hydrologic properties and water quality vary between the distinct units. In addition to the hydrogeologic systems and intervening regional confining units, two distinct hydrogeologic units above the Precambrian basal confining unit are also discussed below.

The ***lower Tertiary/Upper Cretaceous aquifer system*** comprises all Upper Cretaceous and lower Tertiary hydrogeologic units stratigraphically above the thick and widespread Cody regional confining unit. Aquifers within the system are lenticular, discontinuous sandstone bodies that are hydraulically isolated to various degrees by interbedded fine-grained confining units. The hydrogeologic units that compose the ***lower Tertiary/ Upper Cretaceous aquifer system*** above the ***Cody*** *[Major]* ***confining unit*** are, youngest to oldest:

- the Willwood [Minor] aquifer
- the Fort Union [Major Sandstone] aquifer
- the Lance [Major] aquifer
- the Meeteetse aquifer and [Major] confining unit
- the Mesaverde [Major Sandstone] aquifer

Immediately below the ***Cody*** *[Major]* ***confining unit***, the ***lower and middle Mesozoic aquifers and confining units*** system comprises Cretaceous through Jurassic hydrogeologic units. The basal unit of the system, the Nugget Sandstone, might span Triassic and Jurassic time. This hydrogeologic system is composed of [Major], [Minor], and [Marginal] aquifers and confining units dominated by sandstone, siltstone, and shale lithologies. While some of the aquifers are lenticular and discontinuous, the major aquifers are generally more continuous and laterally extensive than those in the ***lower Tertiary/Upper Cretaceous aquifer system*** above the ***Cody confining unit***. The ***lower and middle Mesozoic aquifers and confining units*** include substantial confining units that hydraulically isolate some of the member aquifers. The hydrogeologic units of the system include, from youngest to oldest:

- the Frontier [Minor] aquifer
- the Mowry–Thermopolis [Major] confining unit, including:
  - The Mowry [Major] confining unit
  - The Muddy Sandstone aquifer
  - The Thermopolis [Major] confining unit
- the Cloverly [Major Sandstone] aquifer
- the Morrison confining unit and [Minor] aquifer
- the Sundance confining unit and [Marginal] aquifer
- the Gypsum Spring confining unit and [Marginal] aquifer
- the Nugget [Major Sandstone] aquifer

The Triassic/Permian ***Chugwater-Dinwoody*** *[Marginal]* ***aquifer and confining unit***, *where it contains only the Chugwater aquifer*, separates the overlying ***lower and middle Mesozoic aquifers and confining units*** from the underlying ***Paleozoic aquifer system***. Where the ***Chugwater–Dinwoody*** contains both the Chugwater and Dinwoody hydrogeologic units, the ***Chugwater*** *[Marginal]* ***aquifer*** alone separates the two aquifer systems and the Dinwoody confining unit is included in the Paleozoic aquifer system.

The ***Paleozoic aquifer system*** comprises Permian through Ordovician carbonate and sandstone hydrogeologic units. The hydrogeologic units that compose the ***Paleozoic aquifer system*** are well known for producing high volumes of groundwater at and near the flanks of the Laramide uplifts surrounding the basins where permeability has been structurally enhanced by solution-enlarged fractures. Shale strata within the Phosphoria Formation, the Goose Egg Formation, and the Horseshoe Shale Member of the Amsden Formation constitute the only significant confining units within the ***Paleozoic aquifer system***. The hydrogeologic units that compose the aquifer system are, from youngest to oldest:

- the Goose Egg–Phosphoria [Marginal] aquifer and confining unit or Goose Egg [Marginal] aquifer and confining unit, including:
  - the Dinwoody confining unit [Marginal aquifer]
  - the Phosphoria [Minor] aquifer and confining unit
- the Tensleep aquifer, including:
  - the Tensleep [Major Limestone] aquifer
  - the Ranchester Limestone Member of the Amsden Formation [Marginal aquifer]
- the Amsden confining unit (Horseshoe Shale Member of the Amsden Formation) [Marginal aquifer]
- the Madison–Bighorn [Major Limestone] aquifer, including: a basal confining unit
  - the Madison [Major Limestone] aquifer, including:
  - the Darwin Sandstone Member of the

Amsden Formation [Marginal aquifer]
    - the Madison Limestone [Major Limestone aquifer]
  - the Darby [Major Limestone] aquifer
  - the Bighorn [Major Limestone] aquifer

The ***Paleozoic aquifer system*** is underlain by the Cambrian ***Gallatin–Gros Ventre confining unit***, the Cambrian ***Flathead aquifer***, and the ***Precambrian basal confining unit***:

- the Gallatin–Gros Ventre confining unit, including:
  - the Gallatin confining unit [Minor aquifer
  - the Gros Ventre confining unit [Minor aquifer]
- the Flathead [Major Limestone] aquifer
- the Precambrian basal [Major] confining unit

The Precambrian basement complex is a marginal aquifer locally where it is exposed and fractured in the cores of the uplifts, where thin and disconnected soil, deeply weathered bedrock, and shallow fractures provide transmissive zones. Where these conditions do not exist at land surface, and virtually everywhere in the subsurface, the Precambrian basement is the basal confining unit for the structural groundwater basins in the WBRB and throughout Wyoming.

6.2 Total groundwater resource in the Wind/Bighorn River Basin

One task of this study was to evaluate the available groundwater resource of the WBRB. An enormous quantity of groundwater is stored in the WBRB groundwater basins. However, in addition to the amount of water that an aquifer can sustainably yield, other factors must be considered in determining what part of total stored volume of groundwater may be considered a viable beneficial-use resource, including these:

- Groundwater must be of suitable quality for its intended use.
- The depth to the resource or other accessibility conditions must not preclude groundwater development because of high cost or technical infeasibility.

To address groundwater availability, we evaluate the available (potentially producible) WBRB groundwater resource by calculating:

- Groundwater stored and potentially recoverable within the upper 1,000 feet of the combined Quaternary/Tertiary (Cenozoic) hydrogeologic units in the flat-lying lower-elevation areas of the basins
- Groundwater stored and potentially recoverable within 10- and 20-foot thicknesses of all Quaternary hydrogeologic units exposed in the WBRB
- Average annual recharge (**Figure 5-1**) calculated over aquifers exposed in the WBRB **(Figures 6-3 – 6-6)**

First, for this chapter we define the following *outcrop areas*, to cover the hydrogeologic units mapped on **Plate IV**.

For estimates of stored and available groundwater volume:

Q/T Aquifer	Outcrop areas of combined Quaternary and Tertiary deposits where they are 1,000 feet thick in the WBRB – flat-lying strata covering most of the basin interiors **(Figure 6-3)**
Quaternary Aquifer	Outcrop areas of Quaternary unconsolidated deposits throughout the WBRB, *including* those within the Q/T Aquifer (**Figure 6-2**) area but *excluding* Quaternary and upper Tertiary deposits directly on top of Precambrian rocks

For estimates of recharge:

Q/T Aquifer	As above
Quaternary Aquifer	As above
Mz/Pz Aquifer	Outcrop areas of Mesozoic and Paleozoic deposits – uptilted strata on the flanks of uplifts surrounding the basins **(Figure 6-4)**
p€ Aquifer	Outcrop areas of Precambrian rock – the cores of uplifts surrounding the basins *plus* areas of Precambrian rock overlain *only* by Quaternary unconsolidated deposits and upper Tertiary strata **(Figure 6-6)**
Absaroka Volcanics	Outcrop area of Absoroka volcanic deposits covering the western Bighorn Basin **(Figure 6-5)**

The methodology employed for estimating stored and available groundwater in the Q/T Aquifer, relatively flat-lying

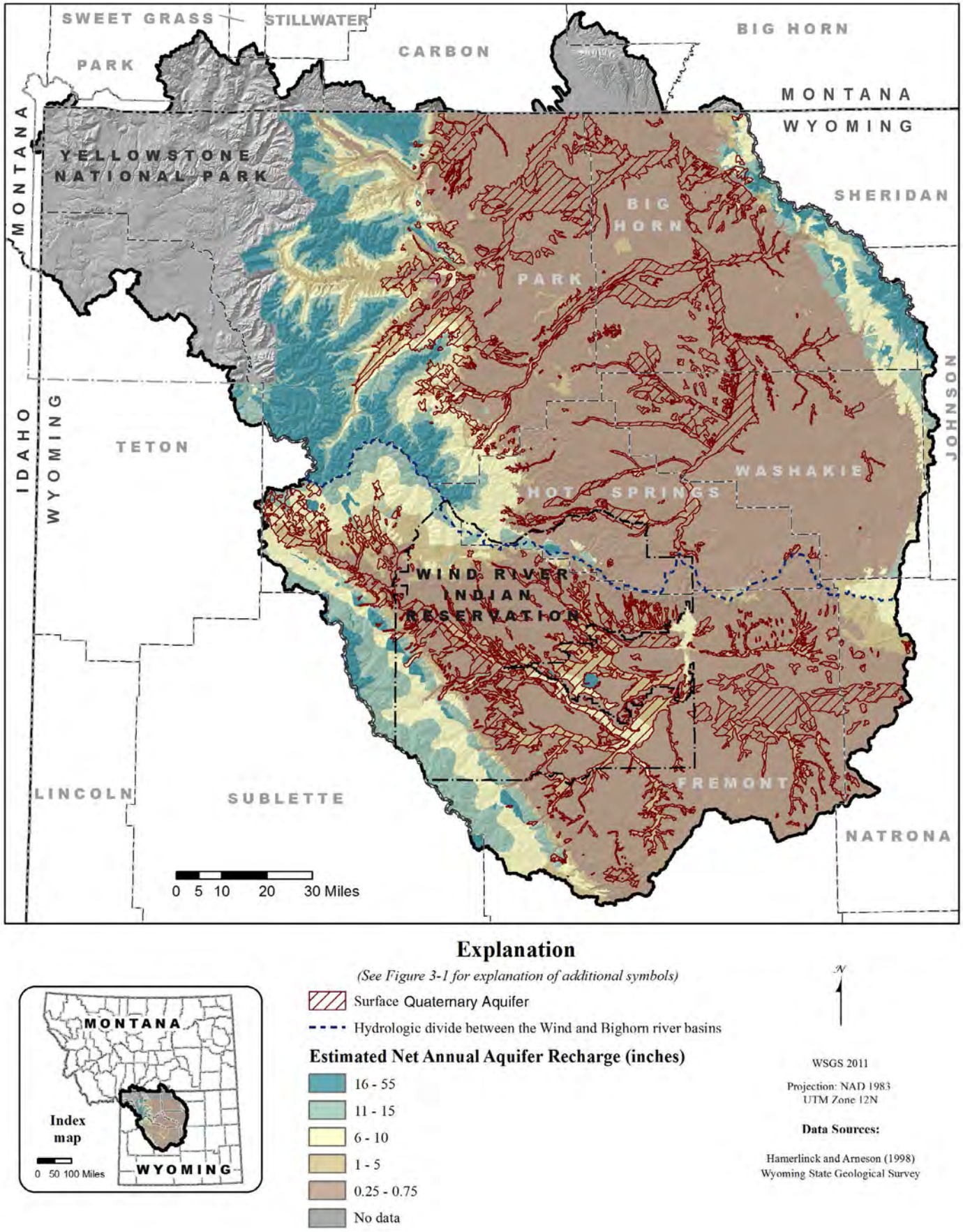


Figure 6-2. Estimated net annual aquifer recharge – surface Quaternary Aquifer, Wyoming Wind/Bighorn River Basin.

hydrogeologic units exposed within the lower-elevation interior areas of the WBRB (**Figure 6-3**), is similar to that used in the recently completed *Available Groundwater Determination for the Greater Green River Basin Technical Memorandum* (Clarey et al., 2010); in addition, we compare stored and available volume estimates with (average annual) recharge. Stored and available groundwater volumes and average annual recharge were also estimated for the Quaternary Aquifer (**Figure 6-2**), for saturated thicknesses of 10 and 20 feet. These estimates of the stored and available groundwater in the Quaternary and Q/T Aquifers neglect recharge and discharge.

For the combined Mesozoic/Paleozoic (Mz/Pz Aquifer) hydrogeologic units and the Precambrian (p€ Aquifer) hydrogeologic units (**Figures 6-4 and 6-6**), as well as the large area of Absaroka Volcanics that borders most of the western Bighorn Basin **(Figure 6-5)**, groundwater resources were evaluated using only average annual recharge. The rationale for using different methodologies is that folding and faulting of the Mz/Pz and p€ Aquifers around the perimeters of the structural basins has affected the distribution and depth of useable groundwater and does not allow assumptions such as a general depth limit for groundwater development. Much of the Absaroka Volcanics terrain is inaccessible; and the highly eroded, complex to chaotic hydrogeologic framework likewise precludes assumptions that allow estimation of groundwater in storage.

6.2.1 WBRB groundwater volume

The groundwater volume estimates for the upper 1000 feet of the WBRB Q/T Aquifer were calculated for the entire stratigraphic volume rather than for individual hydrogeologic units, as adequate data for the more detailed estimates are not available. To account for uncertainty in the grain-size distribution (and associated average porosity), the volume estimates were calculated over a representative range of mixed sand (and coarser) and fine-grained porosities.

Groundwater quality generally deteriorates with depth, due primarily to longer residence time that increases the dissolution of minerals (primarily salts), especially in fine-grained, high-porosity, high-surface-area lithologies that characterize much of the Q/T Aquifer strata in the WBRB. Water quality information for the Q/T Aquifer compiled for this study (**Chapter 7**) generally confirms this observation; however, there are exceptions. In some areas, shallow water has naturally high total dissolved solids (TDS) or is impacted by irrigation and other land uses; and deeper groundwater may exhibit better quality than shallow water in the same area if there is ample recharge with fresh water and vigorous flow some distance into the basin.

For this study a bottom depth of 1,000 feet was used for estimating the available volume of groundwater in the Q/T Aquifer, due to both the general decline in water quality with depth and the greater cost of accessing groundwater at greater depth. The cost of water from wells increases substantially with depth, because of the cost of drilling and constructing a well and the cost of lifting water from greater depth if the confining pressure is not adequate to bring the water close to the surface; however, the cost of extracting water from greater depth may be more than offset by adequate production.

The ranges of stored and available groundwater volumes in the upper 1000 feet of the WBRB Q/T Aquifer was estimated on the basis of the following parameters:

- The surface areas of flat-lying, low-elevation Q/T Aquifers (**Plate IV; Figure 6-3**), totaling 5,975 square miles:
    - the Wind River Basin Q/T Aquifer, 2,885 square miles (80.435×10^9 ft^2)
    - the Bighorn Basin Q/T Aquifer, 3,090 square miles
- An assumed constant total saturated thickness of the Q/T Aquifer of 950 feet, extending from 50 feet below land surface to a depth of 1000 feet:
    - An assumed constant unconfined saturated thickness of 50 feet, extending from 50 feet below land surface to a depth of 100 feet
    - An assumed constant confined saturated thickness of 900 feet, extending from 100 feet below land surface to a depth of 1000 feet
- For total groundwater volume estimates, assumptions on porosity based on published data and specific information compiled for this study for the lithologic characteristics of the geologic units that compose the Q/T Aquifer (Chapter 7, **Plate IX**):
    - 30 percent porosity for sand and coarser-grained lithologies (sand)
    - 35 percent porosity for fine-grained (silt, clay, shale) lithologies (fine)
- For available groundwater volume estimates, assumptions on specific yield and storage coefficients based on published data and information compiled for this study for the lithologic characteristics of the geologic units that compose the Q/T Aquifer (Chapter 7, **Plate IX**): for unconfined groundwater,
    - a specific yield of 26 percent for sand and coarser-grained lithologies (sand)
    - a specific yield of 10 percent for fine-grained lithologies (fine) and for confined groundwater, a storage coefficient of 1×10^{-4} for sand and coarser-grained lithologies (sand)
    - a storage coefficient of 1×10^{-5} for fine-grained lithologies (fine)

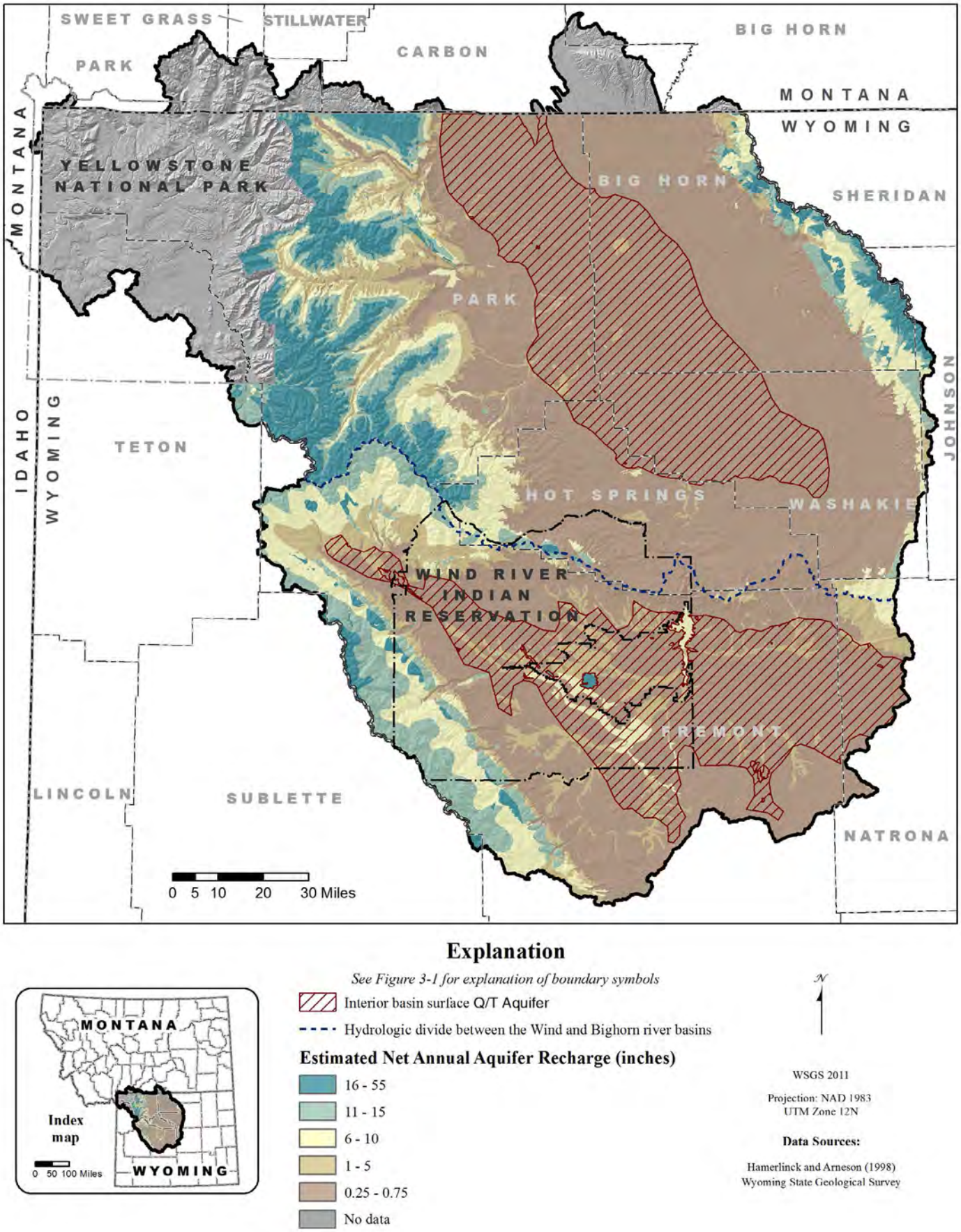


Figure 6-3. Estimated net annual aquifer recharge – interior basin surface Q/T Aquifer, Wyoming Wind/Bighorn River Basin.

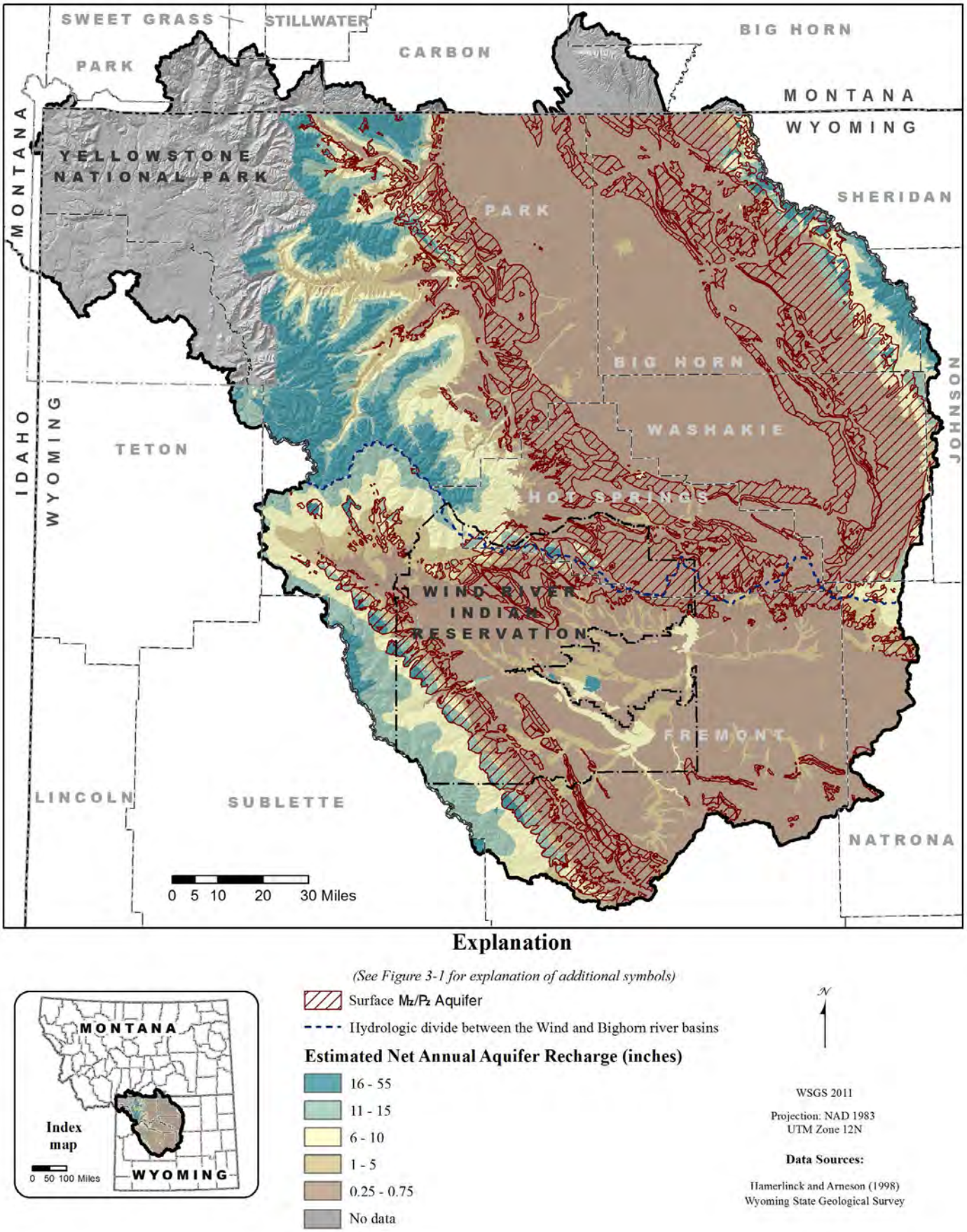


Figure 6-4. Estimated net annual aquifer recharge – surface Mz/Pz Aquifer, Wyoming Wind/Bighorn River Basin.

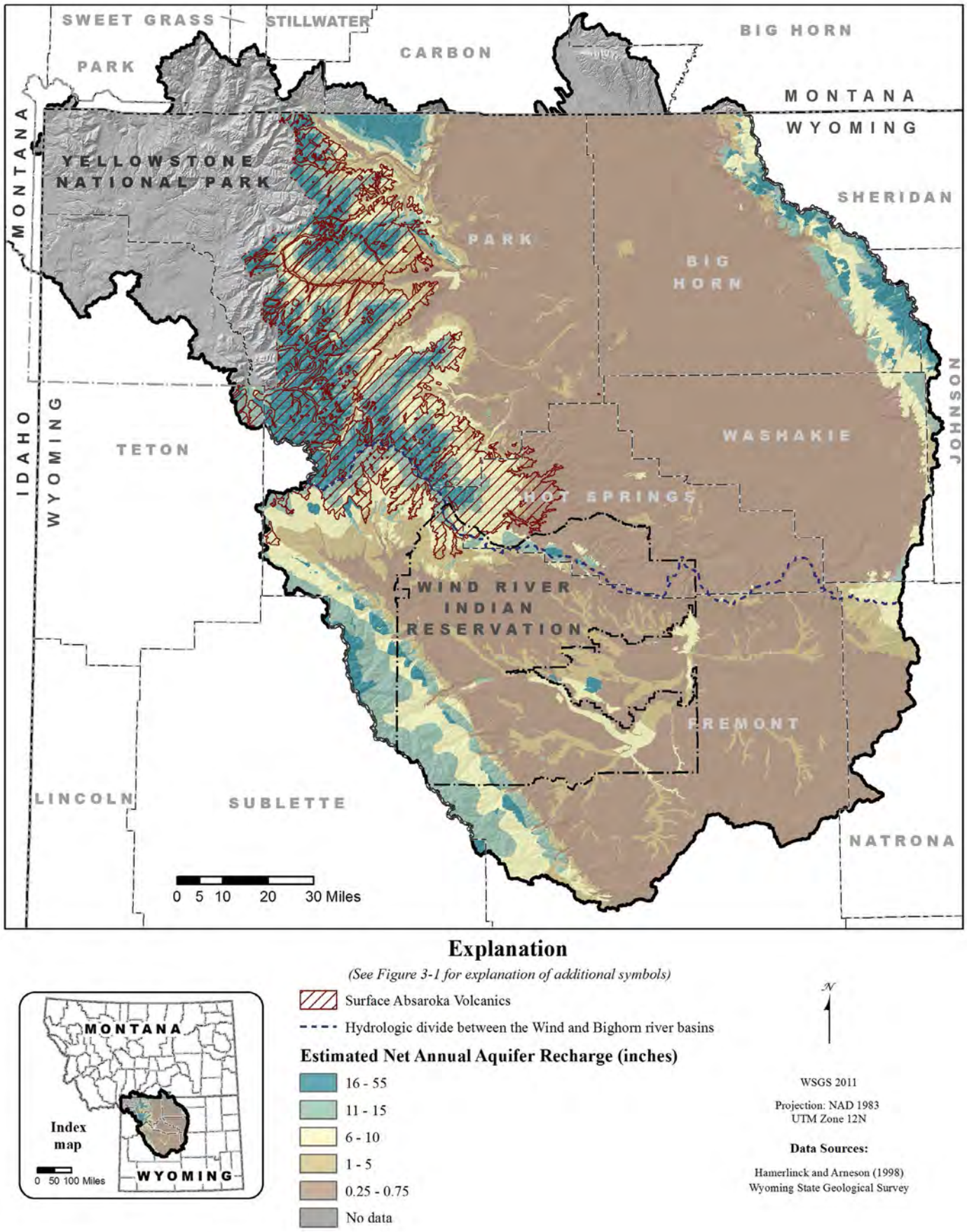
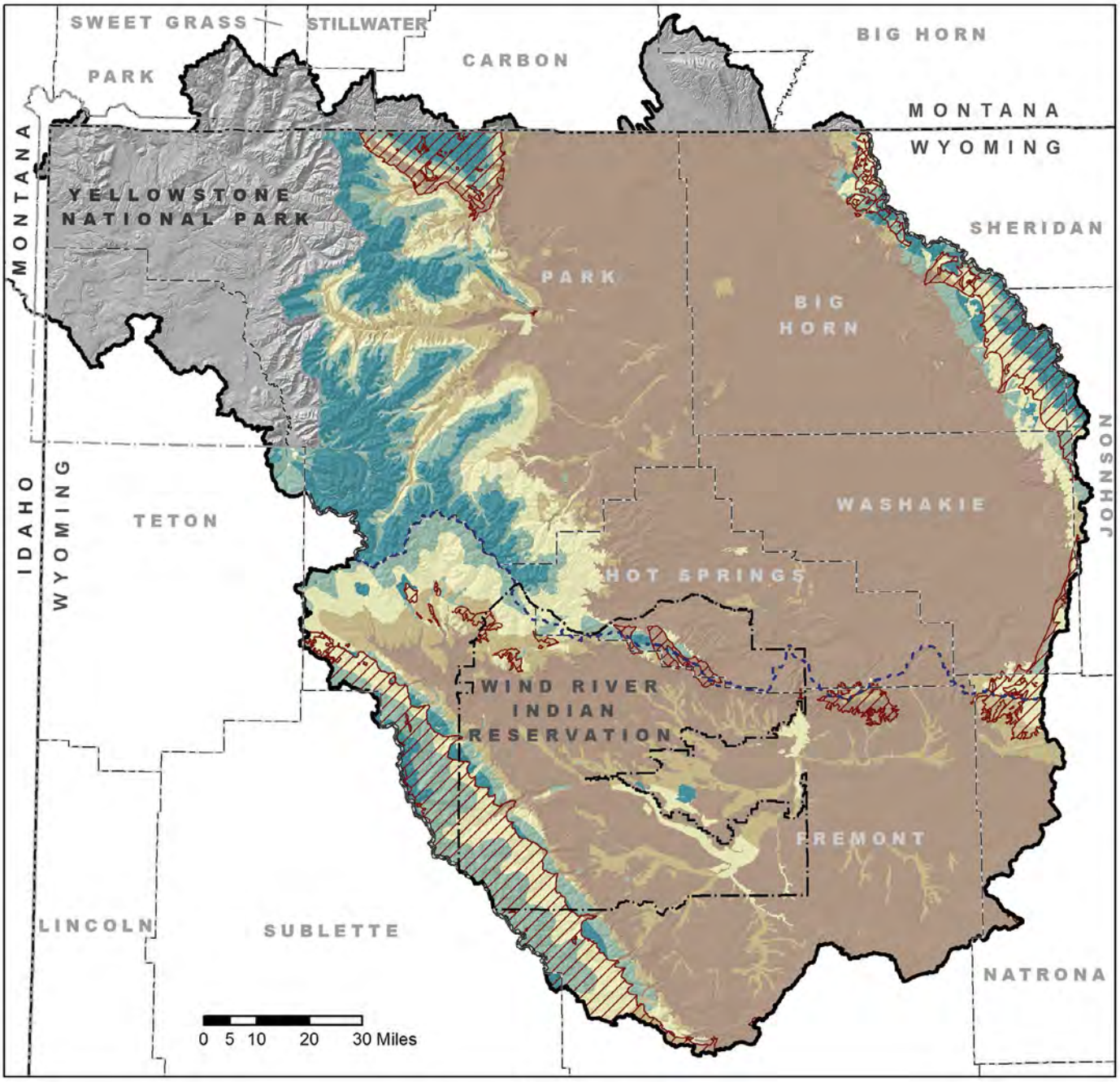


Figure 6-5. Estimated net annual aquifer recharge – surface Absaroka Volcanics, Wyoming Wind/Bighorn River Basin.



Explanation

(See Figure 3-1 for explanation of boundary symbols)

Surface p€ Aquifer

Hydrologic divide between the Wind and Bighorn river basins

Estimated Net Annual Aquifer Recharge (inches)

- 16 - 55
- 11 - 15
- 6 - 10
- 1 - 5
- 0.25 - 0.75
- No data

N

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Hamerlinck and Arneson (1998)
Wyoming State Geological Survey

Figure 6-6. Estimated net annual aquifer recharge – surface p€ Aquifer, Wyoming Wind/Bighorn River Basin.

Similarly, the range of stored and available groundwater volumes in the Quaternary Aquifer was estimated using the following parameters:

- The surface areas of the Quaternary Aquifer (from **Plate IV; Figure 6-2**), totaling 3,198 square miles:
  - the Wind River Basin Quaternary Aquifer, 1,527 square miles
  - the Bighorn Basin Quaternary Aquifer, 1,671 square miles
- Two assumed constant total saturated thicknesses of the Quaternary Aquifer, 10 and 20 feet
- For the total stored groundwater volume estimates, assumptions on porosity based on published data and specific information compiled for this study for the lithologic characteristics of the geologic units that compose the Quaternary Aquifer (Chapter 7, **Plate IX**):
  - 30 percent for sand and coarser-grained lithologies (sand)
  - 35 percent for fine-grained (silt, clay, shale) lithologies (fine)
- For available groundwater volume estimates, assumptions on specific yield based on published data and information compiled for this study for the lithologic characteristics of the geologic units that compose the Quaternary Aquifer (Chapter 7, **Plate IX**):
  - a specific yield of 26 percent for sand and coarser-grained lithologies (sand)
  - a specific yield of 10 percent for fine-grained lithologies (fine)

6.2.1.1 Stored groundwater volume

The total volume of groundwater contained in the pores of the saturated section of the Q/T Aquifer (**Table 6-1**) and the Quaternary Aquifer (**Table 6-2a,b**) is estimated by the general equation

Total groundwater volume
= Area × saturated thickness × porosity

To account for the range of porosity that characterizes the heterogeneous, non-marine lithologies of the Quaternary and Tertiary strata, stored volume estimates were calculated over a range of mixed *sand* (sand and coarser) and *fine* (fine-grained) lithologies, in 10-percent increments from 90 to 10 percent for the sand fraction and from 10 to 90 percent for the corresponding fine fraction. Volumes were estimated separately for the unconfined and confined intervals and for the Wind River and Bighorn Basins. The calculated volumes of stored groundwater contained in the sand and fine fractions were summed to give the volume of groundwater contained in each lithologic mixture.

Groundwater volume general formula:

volume (ft^3) = area (ft^2) × thickness (ft) × porosity (percent as decimal fraction)

For two lithologies, sand and fine:

volume (sand or fine) = area × thickness × percentage (sand or fine) × porosity (sand or fine)

For example, on the basis of porosity, the total *volume of stored groundwater* in the upper 1,000 feet of the Q/T Aquifer in the Wind River Basin with an assumed 40 percent sand, 60 percent fine composition was calculated as follows **(Table 6-1,** highlighted row**)**:

For the unconfined interval:

volume (sand) = 80.435×10^9 ft^2 × 50 ft × 0.40 × 0.30 = 482.610×10^9 ft^3

volume (fine) = 80.435×10^9 ft^2 × 50 ft × 0.60 × 0.35 = 844.569×10^9 ft^3

For the confined interval:

volume (sand) = 80.435×10^9 ft^2 × 900 ft × 0.40 × 0.30 = $8{,}686.922 \times 10^9$ ft^3

volume (fine) = 80.435×10^9 ft^2 × 900 ft × 0.60 × 0.35 = $15{,}202.236 \times 10^9$ ft^3

Total groundwater volume: = $25{,}216.407 \times 10^9$ ft^3

or (1 acre-ft = 43,560 ft^3) = **578.89×10^6 acre-ft**

(We could have combined the unconfined and confined intervals using the 950 feet of saturated thickness in this computation, because the parameters are the same for the unconfined and confined intervals with respect to porosity. We separated the intervals to model how we compute *available* groundwater volume, below, with different parameters for the two intervals – specific yield and storage coefficient.)

We estimate that the total volume of groundwater contained in the water-saturated pores, conduits, openings, and fractures within in the upper 1,000 feet of the Q/T Aquifer is between 535 million and 605 million acre-feet in the Wind River Basin and between 573 million and 648 million acre-feet in the Bighorn Basin **(Table 6-1)**. The total for the WBRB is thus between approximately 1.1 billion and 1.3 billion acre-feet.

The Quaternary Aquifer is assumed to be unconfined; for the two thicknesses considered, the groundwater volume **(Table 6-2)** is given by summing the four permutations of:

Volume (sand or fine, 10 or 20 feet)
= Area × thickness (10 or 20 ft) × percentage (sand or fine) × porosity (sand or fine)

We estimate that the total volume of groundwater contained in the water-saturated pores, conduits, openings, and fractures within in the Quaternary Aquifer is:

- approximately 3.0 to 3.4 million acre-feet (for 10 feet saturated thickness) and approximately 6.0 to 6.7 million acre-feet (for 20 feet saturated thickness) in the Wind River Basin
- approximately 3.3 to 3.7 million acre-feet (for 10 feet saturated thickness) and approximately 6.5 to 7.4 million acre-feet (for 20 feet saturated thickness) in the Bighorn Basin

The estimated total volume of water within the Quaternary Aquifer in the WBRB is thus between approximately 6.3 million and 14.1 million acre-feet.

6.2.1.2 Volume of available groundwater

As described in Section 5.1.4, only a fraction of the groundwater contained in an aquifer is available for use – flows to the surface or can be pumped from wells. While total groundwater volume is estimated on the basis of porosity in both the unconfined and

Table 6-1. Total groundwater volume, WBRB Q/T Aquifer, estimated on porosity (cubic feet, except totals) [ϕ, porosity as decimal fraction; 1 acre-ft = 43,560 ft3].

Wind River Basin					
Lithology mix (%)	**Unconfined volume (ft^3)**		**Confined volume (ft^3)**		**Total volume (acre-ft)**
Sand/fine	**ϕ =0.30 (sand)**	**ϕ=0.35 (fine)**	**ϕ= 0.30 (sand)**	**ϕ= 0.35 (fine)**	
90/10	1,085,874,015,917	140,761,446,508	19,545,732,286,514	2,533,706,037,141	**[1]535,033,833**
80/20	965,221,347,482	281,522,893,016	17,373,984,254,679	5,067,412,074,281	543,804,880
70/30	844,568,679,047	422,284,339,523	15,202,236,222,844	7,601,118,111,422	552,575,926
60/40	723,916,010,612	563,045,786,031	13,030,488,191,009	10,134,824,148,563	561,346,973
50/50	603,263,342,176	703,807,232,539	10,858,740,159,174	12,668,530,185,703	570,118,019
40/60	482,610,673,741	844,568,679,047	8,686,992,127,339	15,202,236,222,844	578,889,066
30/70	361,958,005,306	985,330,125,555	6,515,244,095,505	17,735,942,259,985	587,660,112
20/80	241,305,336,871	1,126,091,572,063	4,343,496,063,670	20,269,648,297,125	596,431,159
10/90	120,652,668,435	1,266,853,018,570	2,171,748,031,835	22,803,354,334,266	**[1]605,202,205**

Bighorn Basin					
Lithology mix (%)	**Unconfined volume (ft^3)**		**Confined volume (ft^3)**		**Total volume (acre-ft)**
Sand/fine	**ϕ =0.30**	**ϕ=0.35**	**ϕ=0.30**	**ϕ=0.35**	
90/10	1,163,027,325,553	150,762,801,461	20,934,491,859,956	2,713,730,426,291	**[1]573,048,953**
80/20	1,033,802,067,158	301,525,602,921	18,608,437,208,850	5,427,460,852,581	582,443,199
70/30	904,576,808,764	452,288,404,382	16,282,382,557,743	8,141,191,278,872	591,837,444
60/40	775,351,550,369	603,051,205,842	13,956,327,906,637	10,854,921,705,162	601,231,689
50/50	646,126,291,974	753,814,007,303	11,630,273,255,531	13,568,652,131,453	610,625,934
40/60	516,901,033,579	904,576,808,764	9,304,218,604,425	16,282,382,557,743	620,020,179
30/70	387,675,775,184	1,055,339,610,224	6,978,163,953,319	18,996,112,984,034	629,414,424
20/80	258,450,516,790	1,206,102,411,685	4,652,109,302,212	21,709,843,410,325	638,808,669
10/90	129,225,258,395	1,356,865,213,145	2,326,054,651,106	24,423,573,836,615	**[1]648,202,915**

[1] Stored volumes, **Table 6-5**

Table 6-2a. Total groundwater volume, WBRB Quaternary Aquifer, 10-ft saturated thickness, estimated on porosity (cubic feet, except totals) [ϕ, porosity as decimal fraction; 1 acre-ft = 43,560 ft3].

Lithology mix (%)	Wind River Basin			Bighorn Basin		
Sand/fine	ϕ = 0.30 (sand)	ϕ = 0.35 (fine)	Total (acre-ft)	ϕ = 0.30 (sand)	ϕ = 0.35 (fine)	Total (acre-ft)
90/10	114,943,667,826	14,900,105,089	[1]**2,980,803**	125,742,107,784	16,299,902,861	[1]**3,260,836**
80/20	102,172,149,179	29,800,210,177	3,029,668	111,770,762,475	32,599,805,722	3,314,292
70/30	89,400,630,531	44,700,315,266	3,078,534	97,799,417,166	48,899,708,583	3,367,749
60/40	76,629,111,884	59,600,420,354	3,127,400	83,828,071,856	65,199,611,444	3,421,205
50/50	63,857,593,237	74,500,525,443	3,176,265	69,856,726,547	81,499,514,305	3,474,661
40/60	51,086,074,589	89,400,630,531	3,225,131	55,885,381,238	97,799,417,166	3,528,118
30/70	38,314,555,942	104,300,735,620	3,273,997	41,914,035,928	114,099,320,027	3,581,574
20/80	25,543,037,295	119,200,840,709	3,322,862	27,942,690,619	130,399,222,888	3,635,030
10/90	12,771,518,647	134,100,945,797	[1]**3,371,728**	13,971,345,309	146,699,125,749	[1]**3,688,486**

[1] Stored volumes, **Table 6-6a**

Table 6-2b. Total groundwater volume, WBRB Quaternary Aquifer, 20-ft saturated thickness, estimated on porosity (cubic feet, except totals) [ϕ, porosity as decimal fraction; 1 acre-ft = 43,560 ft3].

Lithology mix (%)	Wind River Basin			Bighorn Basin		
Sand/fine	ϕ = 0.30 (sand)	ϕ = 0.35 (fine)	Total (acre-ft)	ϕ = 0.30 (sand)	ϕ = 0.35 (fine)	Total (acre-ft)
90/10	229,887,335,652	29,800,210,177	[2]**5,961,606**	251,484,215,569	32,599,805,722	[2]**6,521,672**
80/20	204,344,298,357	59,600,420,354	6,059,337	223,541,524,950	65,199,611,444	6,628,584
70/30	178,801,261,063	89,400,630,531	6,157,068	195,598,834,331	97,799,417,166	6,735,497
60/40	153,258,223,768	119,200,840,709	6,254,799	167,656,143,713	130,399,222,888	6,842,410
50/50	127,715,186,473	149,001,050,886	6,352,531	139,713,453,094	162,999,028,610	6,949,322
40/60	102,172,149,179	178,801,261,063	6,450,262	111,770,762,475	195,598,834,331	7,056,235
30/70	76,629,111,884	208,601,471,240	6,547,993	83,828,071,856	228,198,640,053	7,163,148
20/80	51,086,074,589	238,401,681,417	6,645,724	55,885,381,238	260,798,445,775	7,270,060
10/90	25,543,037,295	268,201,891,594	[2]**6,743,456**	27,942,690,619	293,398,251,497	[2]**7,376,973**

[2] Stored volumes, **Table 6-6b**

confined intervals of an Aquifer, available groundwater volume is estimated on the basis of specific yield in the unconfined interval and storage coefficient in the confined interval of the aquifer. The volume of available groundwater in the Q/T Aquifer and Quaternary Aquifer is estimated by the general equation

Available groundwater volume
= Area × saturated thickness
× specific yield or storage coefficient

To account for the several values of the specific yield or storage coefficient that characterizes the heterogeneous, non-marine lithologies of the Quaternary and Tertiary strata, available volume estimates were calculated over a range of mixed sand and fine lithologies separately for the unconfined and confined intervals, in 10-percent increments from 90 to 10 percent for the sand fraction and from 10 to 90 percent for the corresponding fine fraction, for the Wind River and Bighorn Basins. The calculated volumes of available groundwater contained in the

Available groundwater volume general formula:

volume (ft^3) = area (ft^2) × thickness (ft) × specific yield or storage coefficient (decimal fraction)

For two lithologies, sand and fine:

volume (sand or fine) = area × thickness × percentage (sand or fine) × specific yield (sand or fine)
or storage coefficient (sand or fine)

Table 6-3. Available groundwater volumes, WBRB Q/T Aquifer, unconfined and confined intervals estimated on specific yield and storage coefficient [Sy, Specific yield; S, storage coefficient; 1 acre-ft = 43,560 ft3].

Wind River Basin					
Lithology mix (%)	Unconfined volume (ft^3)		Confined volume (ft^3)		Total volume (acre-ft)
Sand/fine	S_y = 0.26 (sand)	S_y = 0.1 (fine)	S = 0.0001 (sand)	S = 0.00001 (fine)	
90/10	941,090,813,795	40,217,556,145	6,515,244,096	72,391,601	[1]**22,678,972**
80/20	836,525,167,818	80,435,112,290	5,791,328,085	144,783,202	21,186,786
70/30	731,959,521,841	120,652,668,435	5,067,412,074	217,174,803	19,694,600
60/40	627,393,875,863	160,870,224,580	4,343,496,064	289,566,404	18,202,414
50/50	522,828,229,886	201,087,780,725	3,619,580,053	361,958,005	16,710,228
40/60	418,262,583,909	241,305,336,871	2,895,664,042	434,349,606	15,218,043
30/70	313,696,937,932	281,522,893,016	2,171,748,032	506,741,207	13,725,857
20/80	209,131,291,954	321,740,449,161	1,447,832,021	579,132,808	12,233,671
10/90	104,565,645,977	361,958,005,306	723,916,011	651,524,410	[1]**10,741,485**

Bighorn Basin					
Lithology mix (%)	Unconfined volume (ft^3)		Confined volume (ft^3)		Total volume (acre-ft)
Sand/fine	S_y = 0.26 (sand)	S_y = 0.1 (fine)	S = 0.0001 (sand)	S = 0.00001 (fine)	
90/10	1,007,957,015,479	43,075,086,132	6,978,163,953	77,535,155	[1]**24,290,354**
80/20	895,961,791,537	86,150,172,263	6,202,812,403	155,070,310	22,692,145
70/30	783,966,567,595	129,225,258,395	5,427,460,853	232,605,465	21,093,937
60/40	671,971,343,653	172,300,344,526	4,652,109,302	310,140,620	19,495,729
50/50	559,976,119,711	215,375,430,658	3,876,757,752	387,675,775	17,897,520
40/60	447,980,895,769	258,450,516,790	3,101,406,201	465,210,930	16,299,312
30/70	335,985,671,826	301,525,602,921	2,326,054,651	542,746,085	14,701,104
20/80	223,990,447,884	344,600,689,053	1,550,703,101	620,281,240	13,102,895
10/90	111,995,223,942	387,675,775,184	775,351,550	697,816,395	[1]**11,504,687**

[1] Available volume, **Table 6-5**

sand and fine fractions were summed to give the volume of available groundwater in each lithologic mixture.

For example, the total volume of available groundwater in the upper 1,000 feet of the Q/T Aquifer in the Wind River Basin on the basis of specific yield or storage coefficient and with an assumed 40 percent sand and 60 percent fine composition was calculated as follows **(Table 6-3, highlighted row)**:

We estimate that the total volume of available groundwater in the upper 1,000 feet of the Q/T Aquifer is between approximately 10.7 million and 22.7 million acre-feet in the Wind River Basin and between 11.5 million and 24.3 million acre-feet in the Bighorn Basin. The estimated total groundwater volume in the WBRB is thus between approximately 22.2 million and 47.0 million acre-feet. (These are the low and high estimates given in **Table 6-5**.)

For the unconfined interval:

volume (sand) = 80.435×10^9 $ft^2 \times 50ft \times 0.40 \times 0.26$ = 418.26×10^9 ft^3

volume (fine) = 80.435×10^9 $ft^2 \times 50ft \times 0.60 \times 0.10$ = 241.31×10^9 ft^3

For the confined interval:

volume (sand) = 80.435×10^9 $ft^2 \times 900ft \times 0.40 \times 0.0001$ = 2.8957×10^9 ft^3

volume (fine) = 80.435×10^9 $ft^2 \times 900ft \times 0.60 \times 0.00001$ = 0.43435×10^9 ft^3

Total available groundwater volume = 662.90×10^9 ft^3

or (1 acre-ft = 43,560 ft^3) = **15.218×16^6 acre-ft**

Table 6-4a. Available groundwater volume, WBRB Quaternary Aquifer, 10-ft saturated thickness, estimated on specific yield (cubic feet, except totals).

Lithology mix (%)	Wind River Basin			Bighorn Basin		
Sand/fine	**ϕ = 0.30 (sand)**	**ϕ = 0.35 (fine)**	**Total (acre-ft)**	**ϕ = 0.30 (sand)**	**ϕ = 0.35 (fine)**	Total (acre-ft)
90/10	99,617,845,449	4,257,172,882	[1]2,384,642	108,976,493,413	4,657,115,103	**[1]2,608,669**
80/20	88,549,195,955	8,514,345,765	2,228,272	96,867,994,145	9,314,230,206	2,437,608
70/30	77,480,546,461	12,771,518,647	2,071,902	84,759,494,877	13,971,345,309	2,266,548
60/40	66,411,896,966	17,028,691,530	1,915,532	72,650,995,609	18,628,460,413	2,095,488
50/50	55,343,247,472	21,285,864,412	1,759,162	60,542,496,341	23,285,575,516	1,924,428
40/60	44,274,597,977	25,543,037,295	1,602,792	48,433,997,073	27,942,690,619	1,753,367
30/70	33,205,948,483	29,800,210,177	1,446,422	36,325,497,804	32,599,805,722	1,582,307
20/80	22,137,298,989	34,057,383,060	1,290,052	24,216,998,536	37,256,920,825	1,411,247
10/90	11,068,649,494	38,314,555,942	[1]1,133,682	12,108,499,268	41,914,035,928	**[1]1,240,187**

[1] Available volume, **Table 6-6a**

Table 6-4b. Available groundwater volume, WBRB Quaternary Aquifer, 20-ft saturated thickness, estimated on specific yield (cubic feet, except totals) [Sy, Specific yield; 1 acre-ft = 43,560 ft3].

Lithology mix (%)	Wind River Basin			Bighorn Basin		
Sand/fine	**ϕ = 0.30 (sand)**	**ϕ = 0.35 (fine)**	**Total (acre-ft)**	**ϕ = 0.30 (sand)**	**ϕ = 0.35 (fine)**	**Total (acre-ft)**
90/10	199,235,690,899	8,514,345,765	[2]4,769,285	217,952,986,826	9,314,230,206	**[2]5,217,337**
80/20	177,098,391,910	17,028,691,530	4,456,545	193,735,988,290	18,628,460,413	4,875,217
70/30	154,961,092,921	25,543,037,295	4,143,805	169,518,989,754	27,942,690,619	4,533,096
60/40	132,823,793,932	34,057,383,060	3,831,065	145,301,991,218	37,256,920,825	4,190,976
50/50	110,686,494,944	42,571,728,824	3,518,325	121,084,992,681	46,571,151,031	3,848,855
40/60	88,549,195,955	51,086,074,589	3,205,585	96,867,994,145	55,885,381,238	3,506,735
30/70	66,411,896,966	59,600,420,354	2,892,845	72,650,995,609	65,199,611,444	3,164,614
20/80	44,274,597,977	68,114,766,119	2,580,105	48,433,997,073	74,513,841,650	2,822,494
10/90	22,137,298,989	76,629,111,884	[2]2,267,365	24,216,998,536	83,828,071,856	**[2]2,480,374**

[2] Available volume, **Table 6-6b**

The Quaternary Aquifer is assumed to be unconfined; and for the two thicknesses considered, the available groundwater volume **(Table 6-4)** is given by summing permutations of

Volume (sand or fine, 10 or 20 ft)
= Area × thickness (10 or 20 ft) × percentage (sand or fine)
× specific yield (sand or fine)

We estimate that the total volume of available groundwater in the Quaternary Aquifer is between approximately 1.1 million and 4.8 million acre-feet in the Wind River Basin and between 1.2 million and 5.2 million acre-feet in the Bighorn Basin:

- 1.1 to 2.4 million acre-feet (for 10-foot saturated thickness) and 2.3 to 4.8 million acre-feet (for 20 foot saturated thickness) in the Wind River Basin,
- 1.2 to 2.6 million acre-feet (for 10-foot saturated thickness) and 2.5 to 5.2 million acre-feet (for 20 foot saturated thickness) in the Bighorn Basin.

The estimated volume of available groundwater in the Quaternary Aquifer in the WBRB is thus between approximately 2.4 million and 10 million acre-feet. (These are the low and high estimates given in **Tables 6-6a and 6-6b**.)

6.2.1.3 Discussion of stored and available groundwater estimates

Tables 6-5 and **6-6a, b** summarize our estimates of stored and available groundwater volumes in the Q/T and Quaternary Aquifers in the Wind River Basin, the Bighorn Basin, and the WBRB. The high and low volume estimates correspond to the 90/10 and 10/90 sand/fine percentages. The tables comprise:

Table 6-5. Summary – Estimates and comparison of stored and available groundwater volumes, WBRB Q/T Aquifer.

Parameter		Groundwater volume (million acre-ft)		
		Wind River Basin	**Bighorn Basin**	**WBRB total**
Stored volume	**90% sand / 10% fine**	[1]535.03	[1]573.05	1,108.08
	10% sand / 90% fine	[1]605.20	[1]648.20	1,253.40
	difference	70.17	75.15	145.32
	percent, low/high	88.4%		
Available volume	**90% sand / 10% fine**	[2]22.68	[2]24.29	46.97
	10% sand / 90% fine	[2]10.74	[2]11.50	22.25
	difference	11.94	12.79	24.72
	percent, low/high	47.4%		
Comparison, available/stored	**Difference, 90/10**	512.35	548.76	1,061.11
	Difference, 10/90	594.46	636.70	1,231.16
	percent, available/stored, 90/10	4.2%		
	percent, available/stored, 10/90	1.8%		

[1] From **Table 6-1** [2] From **Table 6-3**

- For stored groundwater (based on porosity): high and low volume estimates, their difference, and the low estimate as a percentage of the high estimate
- For available groundwater (by specific yield and storage coefficient): high and low volume estimates, their difference, and the low estimate as a percentage of the high estimate
- To compare available with stored groundwater: for the high and low volume estimates, the difference between available and stored groundwater; and available groundwater as a percentage of stored groundwater.

Predictably, **Tables 6-5 and 6-6a,b** show that the amount of stored groundwater is greater in the 10/90 mix of sand/fine porosity than in the 90/10 mix, because fine-grained lithologies have higher porosity. Conversely, the volume of available groundwater is higher in the 90/10 mix, because sand and coarser-grained lithologies have higher values for specific yield and storage coefficient than fine-grained lithologies (Section 5.1.4). This exercise shows that for the calculation of stored groundwater in storage in a heterogeneous aquifer with mixed sand/fine lithologies, it is not critical to have precise information on the mix proportions, as the low estimates are close to (88 percent of) the high estimates. Knowledge of the mix of sand/fine lithologies is more important in estimating available groundwater; the low estimates are 47-48 percent of the high estimates.

Table 6-5 also shows that in the Q/T Aquifer the volume of available groundwater for the 90/10 and 10/90 mixes of sand/fine lithology are between 1.8 and 4.2 percent, respectively, of the stored groundwater from 50 to 1,000 feet below the land surface. (A 50/50 sand/fine mix gives an available/stored ratio of 3.0 percent, the conventional value; and the 1.8 percent and 4.2 percent values bracket it nicely, and may be applicable in areas of local lithologic homogeneity.) In contrast, available groundwater as a fraction of stored groundwater in the Quaternary Aquifer is between 80 percent (90/10 mix) and 33.6 percent (10/90 mix) for both 10 and 20 feet of saturated thickness. The large difference between the ratios of available/stored groundwater in the Q/T Aquifer and the Quaternary Aquifer arises because the great amount of groundwater stored in the 950 feet of saturated thickness in the Q/T Aquifer is assumed to be mostly confined and to yield water as a function of a storage coefficient that is three to four orders of magnitude smaller than the specific yield of the saturated thickness of the Quaternary Aquifer.

6.2.2 Average annual recharge

As shown in the preceding section, although the saturated geologic units in the groundwater basins function as reservoirs that store enormous volumes of groundwater, with the exception of unconfined aquifers (primarily Quaternary strata) only a small fraction of the groundwater in storage can be withdrawn for beneficial use. If only the volume of potentially producible water in storage were considered, it would clearly be a non-renewable resource. The amount of groundwater withdrawal

Table 6-6a. Summary - Estimates of stored and available groundwater volumes in the WBRB Quaternary Aquifer, 10-ft saturated thickness.

Parameter		Groundwater volume (million acre-ft)		
		Wind River Basin	**Bighorn Basin**	**WBRB total**
Stored volume	**90% sand / 10% fine**	[1]2.98	[1]3.26	6.24
	10% sand / 90% fine	[1]3.37	[1]3.69	7.06
	difference	0.39	0.43	0.82
	percent, low/high	88.4%		
Available volume	**90% sand / 10% fine**	[2]2.38	[2]2.61	4.99
	10% Sand / 90% Fine	[2]1.13	[2]1.24	2.37
	difference	1.25	1.37	2.62
	percent, low/high	47.5%		
Comparison, available/stored	**Difference, 90/10**	0.60	0.65	1.25
	Difference, 10/90	2.24	2.45	4.69
	percent, available/stored, 90/10	80.0%		
	percent, available/stored, 10/90	33.6%		

[1] From Table 6-2a [2] From Table 6-4a

Table 6-6b. Summary - Estimates of stored and available groundwater volumes in the WBRB Quaternary Aquifer, 20-ft saturated thickness.

Parameter		Groundwater volume (million acre-ft)		
		Wind River Basin	**Bighorn Basin**	**WBRB total**
Stored volume	**90% sand / 10% fine**	[1]5.96	[1]6.52	12.48
	10% sand / 90% fine	[1]6.74	[1]7.38	14.12
	difference	0.78	0.86	1.64
	percent, low/high	88.4%		
Available volume	**90% sand / 10% fine**	[2]4.77	[2]5.22	9.99
	10% sand / 90% fine	[2]2.27	[2]2.48	4.75
	difference	2.50	2.74	5.24
	percent, low/high	47.5%		
Comparison available/stored	**Difference, 90/10**	1.19	1.30	2.50
	Difference, 10/90	4.48	4.90	9.37
	percent, available/stored, 90/10	80.0%		
	percent, available/stored, 10/90	33.6%		

[1] From **Table 6-2b** [2] From **Table 6-4b**

that can be sustained from a typical aquifer system is controlled by recharge, most strongly as withdrawal approaches or exceeds recharge.

The availability of average annual recharge from Hamerlinck and Arneson (1998) and our mapping of the outcrop areas of the hydrogeologic units in the WBRB **(Figure 5-1 and Plate IV)** provided the opportunity to evaluate recharge on a regional

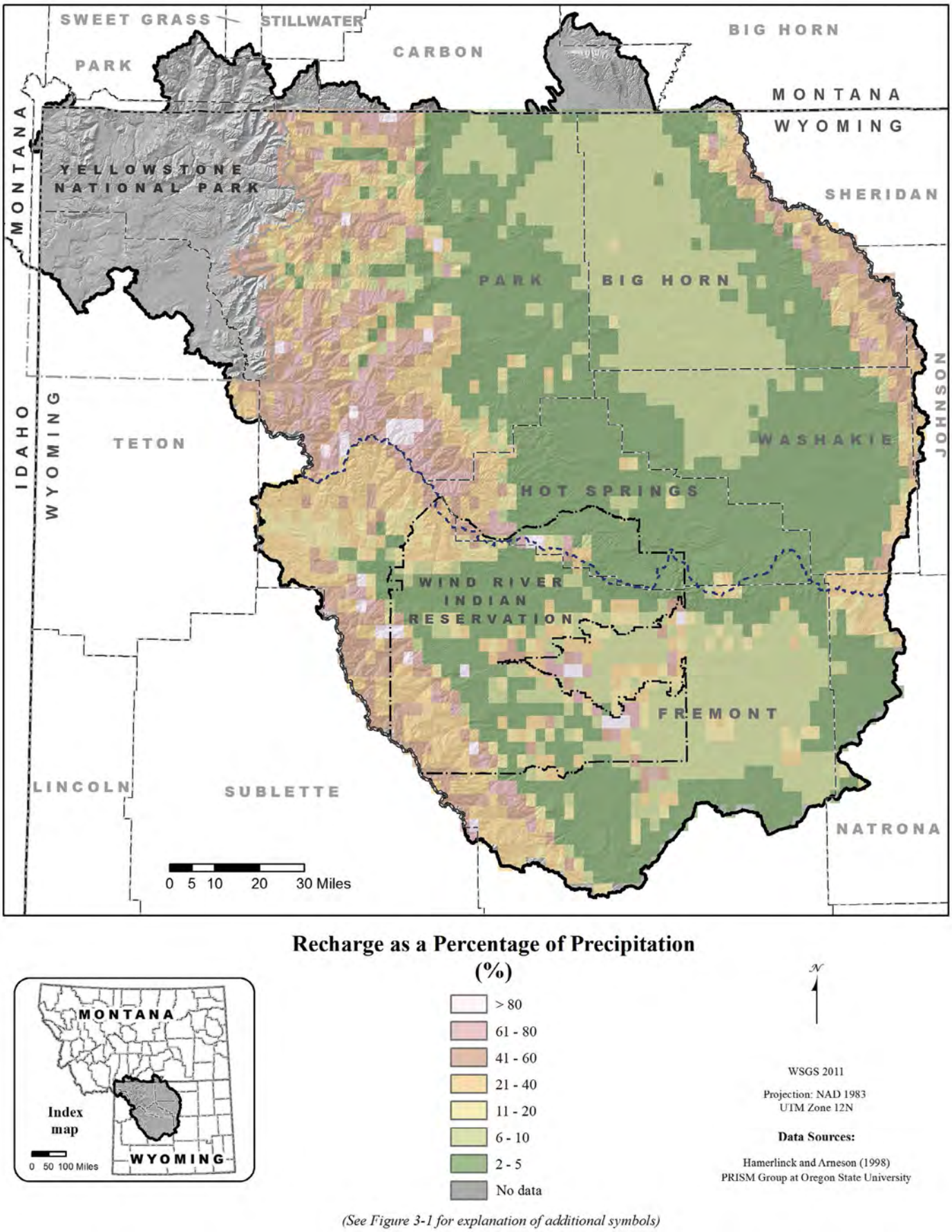


Figure 6-7. Aquifer recharge as percentage of precipitation, Wyoming Wind/Bighorn River Basin.

Table 6-7. Percentages of the seven recharge-efficiency ranges that cover the outcrop areas defined for this study, Wind River and Bighorn basins, Wyoming [Recharge efficiency ranges, Figure 6-7; outcrop areas, Figures 6-2 through 6-6].

		Wind River Basin							Bighorn Basin						
		Recharge efficiency[1] range (percent)													
		2-5	6-10	11-20	21-40	41-60	61-80	>80	2-5	6-10	11-20	21-40	41-60	61-80	>80
Outcrop area	Quaternary Aquifer	27.2	33.9	14.0	15.2	4.4	3.1	2.1	38.3	50.4	2.0	4.9	2.7	1.3	0.4
	Q/T Aquifer	28.0	48.1	10.1	7.6	2.7	2.6	1.0	43.4	55.9	0.5	0.3	0.0	0.0	0.0
	Mz/Pz Aquifer	51.4	6.3	12.2	11.0	12.1	5.2	1.7	66.0	13.2	3.4	9.7	5.3	2.1	0.3
	Absaroka Volcanics	0.0	0.0	5.0	77.8	13.3	3.5	0.4	6.3	3.8	6.6	28.3	34.6	17.4	3.0
	pЄ Aquifer	4.5	0.3	6.3	54.8	30.2	2.0	1.9	7.8	3.6	6.0	35.9	38.3	6.7	1.6

[1] Recharge (**Figures 6-2 – 6-6**) as a percentage of precipitation (**Figure 5-1**)

scale that has not been attempted previously. This section describes how the volume of average annual recharge within the WBRB groundwater basin was estimated and evaluated for this study.

Aquifer-specific average annual recharge less estimated present annual discharge (both natural and by pumping) establishes an estimate of how much groundwater development can be sustained without unacceptably drawing down storage or causing permanent structural damage (irreversible compression of a confined aquifer). Recharge is estimated in this study; however, discharge is difficult to estimate, especially on an aquifer-specific basis. BRS Inc. (2003e) and MWH et al. (2010) developed estimates of annual groundwater withdrawals and consumptive uses that are used in this study **(Chapter 8)**. MWH et al. also developed a water-balance for the WBRB drainage basin. Comparison of recharge with stored and available groundwater volumes (this section); analysis of recharge as percentages of precipitation and of other basin-wide water balance statistics; and current groundwater consumptive use and future groundwater requirements as a percentage of recharge **(Chapter 8)** also contribute to this inventory of WBRB groundwater resources.

Estimated average annual recharge in the WBRB ranges from less than 1 inch per year in interior areas of the basins to more than 55 inches per year in the surrounding mountains **(Figure 5-1)**. The mountain and foothill areas are characterized by higher recharge than the lowlands in the basins because of:

- greater precipitation and more persistent snow pack
- more abundant vegetation
- soil and vegetation combinations more favorable to infiltration
- less evapotranspiration
- better exposure of the upturned and eroded edges of hydrogeologic units and associated greater permeability parallel to bedding
- structural features that enhance recharge: faults, fractures, fault/fracture-controlled surface drainage

Figure 6-7, a map of *recharge efficiency* (recharge as a percentage of precipitation), illustrates more efficient recharge in the highlands surrounding the basins. **Figure 6-7** was compiled to show how the recharge efficiency varies over the WBRB and to inform speculation on the factors that control recharge. The figure shows areas of recharge efficiency, grouped in ranges, each area containing the set of 4,000-meter grid cells with recharge efficiencies within a given range. The recharge efficiency in each grid cell was calculated by dividing the average annual recharge to the cell (see **Figure 5-1**) by the average annual precipitation to the cell (see **Figure 3-3**). **Figure 5-1,** average annual recharge, is based on percolation percentages for different soil/vegetation combinations multiplied by precipitation to give average annual recharge. Although this does not take all the factors that affect recharge into consideration, initial infiltration and precipitation are probably the most important in a regional sense, and the other factors listed above and in **Section 5.1.3.1** should confirm the general pattern of recharge efficiency displayed in **Figure 6-7**. As discussed previously **(Sections 5.1.3.1 and 5.4)**, local recharge may be dominated by site-specific hydrogeologic conditions, such as solution-enhanced fracture permeability.

In adapting **Figure 5-1** from Hamerlinck and Arneson, 1998, and developing **Figure 6-7**, all recharge values less than or equal to zero were changed to 0.5 inches prior to performing the calculation. This change was made for most of the cells within the interior basins areas, and therefore has a strong influence on the appearance of both maps in these areas. The resulting

Table 6-8a. Estimated average annual recharge to Wind River Basin outcrop areas [Shaded values recapitulated in Table 6-9].

Outcrop area	Range, average recharge per year (inches)	Area of outcrop receiving recharge (feet²)	Average annual recharge (acre-feet)	
			Range	Best total
Quaternary Aquifer	0.25 0.75	21,006,344,056	10,047 30,142	20,095
	1 5	16,323,546,734	31,230 156,151	92,923
	6 10	4,694,431,824	53,888 89,814	63,510
	11 15	496,231,617	10,443 14,241	11,331
	16 28	51,174,594	1,567 2,741	1,919
Low			107,176	
High			293,090	
Quaternary Aquifer		42,571,728,824		189,778
QT Aquifer	0.25 0.75	66,000,645,129	31,568 94,704	63,136
	1 5	11,565,235,866	22,127 110,633	61,568
	6 10	2,827,018,365	32,452 54,087	35,216
	11 15	19,306,495	406 554	487
	16 24	22,906,435	701 1,052	842
Low			87,254	
High			261,030	
Q/T Aquifer		80,435,112,290		161,250
Mz/Pz Aquifer	0.25 0.75	22,388,614,335	10,708 32,125	21,417
	1 5	4,521,148,311	8,650 43,249	35,321
	6 10	2,760,879,493	31,693 52,821	48,967
	11 15	5,031,359,192	105,886 144,390	120,081
	16 32	1,984,707,699	60,754 121,509	69,886
Low			217,692	
High			394,095	
Mz/Pz Aquifer		36,686,709,030		295,671
pЄ Aquifer	0.25 0.75	1,907,097,054	912 2,736	1,824
	1 5	3,196,800,892	6,116 30,581	26,464
	6 10	11,501,597,242	132,029 220,049	185,841
	11 15	12,379,760,013	260,535 355,275	294,107
	16 55	1,567,328,560	47,978 164,924	59,899
Low			447,570	
High			**773,565**	
pЄ Aquifer		**30,552,583,761**		**568,136**

Table 6-8a. Continued.

Outcrop area	Range, average recharge per year (inches)	Area of outcrop receiving recharge (feet²)	Average annual recharge (acre-feet)	
			Range	Best total
Absaroka Volcanics	1 5	270,738,515	518 2,590	2,590
	6 10	3,153,779,422	36,203 60,338	50,771
	11 15	3,967,404,927	83,495 113,857	94,553
	16 47	31,521,050	965 2,834	1,276
Low			**121,181**	
High			**179,619**	
Absaroka Volcanics		**7,423,443,914**		**149,190**
Wind River Basin		**171,296,356,412**	**923,533** **1,734,880**	**1,264,027**

large area of constant recharge in the interior basin areas is clearly shown on **Figure 5-1**. The higher range of recharge/precipitation (R/P) in the central, driest areas of the basin than around the basin perimeter shown on **Figure 6-7** is the result of a constant recharge value divided by lower precipitation values in the interior basin areas. The original data from Hamerlinck and Arneson (1998) that showed most of the interior basin areas receiving no recharge (including some outlier negative values) was changed for this report because it is well known that shallow groundwater occurs in both the alluvial and bedrock aquifers throughout the interior lowlands of both the Wind River and Bighorn basins. If no recharge were occurring in these areas, shallow groundwater could not be sustained. Therefore, a conservative low range of recharge (0.25 to 0.75 inches) was used for volume calculations, and the average (0.5 inches) was used for developing **Figures 5-1 and 6-7**.

Table 6-7 is a matrix of the percentages of aquifer outcrop (recharge) areas that are recharged within various ranges of recharge efficiency. The aquifer outcrop areas are the same as those used to calculate recharge volumes **(Figures 6-2 through 6-6)**. The highlighted areas of **Table 6-7** indicate the dominant ranges of recharge efficiency characteristic of each aquifer – and point to the factors (precipitation and vegetation/soil types) that control recharge (based on the presentation of Hamerlinck and Arneson, 1998).

Table 6-7 shows that recharge to the sedimentary aquifers occurs primarily at lower recharge efficiencies (2 percent to 20 percent), with areas of the Quaternary Aquifer in the Wind River Basin and the Mz/Pz Aquifer recharging at higher efficiencies (21 percent to 40 percent). In contrast, recharge in the Absaroka volcanic and Precambrian crystalline terrains occurs mostly at 21 percent to 60 percent efficiencies, with a significant area of the Absaroka Volcanics recharging at 61 percent to 80 percent of precipitation. This pattern is consistent with the criteria of Hamerlinck (1998) for mapping average annual recharge based on precipitation and vegetation/soil type, with the amount of both (and consequent favorable soil development) increasing with elevation and proximity to the uplifted areas surrounding the basins (Hamerlink and Arneson, 1998). As in the map of recharge efficiency **(Figure 6-7)**, the change of cell values that were zero or negative to 0.5 inches is reflected in **Table 6-7**.

The estimation of total recharge provided in this section is somewhat at odds with the water resources mass balance for the WBRB prepared by MWH (2010a), with a higher volume of water going into recharge than the balance seems to allow **(Chapter 8)**. However, much of the recharge to the Precambrian and volcanic areas (which are characterized by the highest recharge efficiencies and account for a large part of overall recharge) is generally quickly discharged to surface waters as rejected recharge. Much of this volume can be deducted from the overall recharge – it is measured in surface flow and not retained in storage. A more comprehensive statewide analysis of recharge that included factors not used by Hamerlinck and Arneson (1998) (e.g., slope, structure, evaporation) and natural discharge (e.g., rejected recharge) would help refine the analysis of recharge presented in this study.

For this study the volume of average annual recharge in the WBRB was calculated for the Quaternary Aquifer, for the Q/T Aquifer, for the Mz/Pz and p€ Aquifers, and for the Absaroka Volcanics, all separately, for the Wind River and Bighorn basins. Because total stored groundwater was also estimated for the Q/T Aquifer and the Quaternary Aquifer, a useful comparison can be made of stored groundwater with average annual recharge in these outcrop areas.

Only average annual recharge is used in evaluating groundwater resources in the Mz/Pz, and p€ Aquifers and the Absaroka Volcanics. A comparison with total groundwater in storage, similar to the Q/T Aquifer evaluation, is not practical for the Mz/Pz Aquifer because it is not flat-lying, and so is not

Table 6-8b. Estimated average annual recharge to Bighorn Basin outcrop areas [Shaded values recapitulated in Table 6-9].

Outcrop area	Range, average recharge per year (inches)	Area of outcrop receiving recharge (feet²)	Average annual recharge (acre-feet)		
			Range		Best total
Quaternary Aquifer	0.25 0.75	38,091,977,130	18,219	54,658	36,439
	1 5	5,249,074,268	10,043	50,213	19,906
	6 10	2,803,172,842	32,178	53,630	38,242
	11 15	407,394,017	8,574	11,691	9,384
	16 42	19,532,773	598	1,570	659
Low			69,612		
High				171,762	
Quaternary Aquifer		46,571,151,031			104,629
QT Aquifer	0.25 0.75	84,777,282,580	40,549	121,647	81,098
	1 5	1,366,686,075	2,615	13,074	4,918
	6 9	6,203,608	71	107	92
Low			43,235		
High				134,828	
Q/T Aquifer		86,150,172,263			86,108
Mz/Pz Aquifer	0.25 0.75	73,233,215,453	35,027	105,082	70,055
	1 5	3,965,737,287	7,582	37,936	16,052
	6 10	6,441,974,868	73,949	123,248	104,873
	11 15	4,843,948,582	101,942	139,012	118,187
	16 38	2,612,266,849	79,965	189,916	98,883
Low			298,470		
High				595,195	
Mz/Pz Aquifer		91,097,143,040			408,050
p€ Aquifer	0.25 0.75	2,842,907,462	1,360	4,079	2,720
	1 5	1,296,160,726	2,480	12,399	5,149
	6 10	6,299,479,819	72,313	120,522	103,223
	11 15	3,813,807,780	80,262	109,449	91,686
	16 46	6,405,372,756	196,076	563,720	247,524
Low			352,492		
High				810,169	
p€ Aquifer		20,657,728,543			450,302
Absaroka Volcanics	0.25 0.75	2,562,637,349	1,226	3,677	2,451
	1 5	5,849,464,884	11,191	55,956	22,886
	6 10	14,364,670,088	164,895	274,825	212,345
	11 15	16,085,308,135	338,519	461,617	401,010
	16 44	27,180,955,790	832,043	2,288,118	1,110,602
Low			**1,347,874**		
High				**3,084,193**	
Absaroka Volcanics		**66,043,036,247**			**1,749,295**
Bighorn Basin		**288,951,933,980**	**2,101,042**	**4,763,357**	**2,776,769**

Table 6-9. WBRB total average annual recharge.

Basin	Outcrop area	[1]Annual recharge (acre-feet)		[2]Percentage of total WBRB precipitation	
		Range	Best total	Range	Best
Wind River Basin	Quaternary Aquifer	107,176 – 293,090	189,778	0.6-1.6%	1.0%
	Q/T Aquifer	87,254 – 261,030	161,250	0.5-1.4%	0.9%
	Mz/Pz Aquifer	217,692 – 394,095	295,671	1.2-2.1%	1.6%
	p€ Aquifer	447,570 – 773,565	568,136	2.4-4.2%	3.1%
	Absaroka Volcanics	121,181 – 179,619	149,190	0.7-1.0%	0.8%
	Low total	923,533	1,264,027	5.0-9.4%	6.8%
	High total	1,734,880			
Bighorn Basin	Quaternary Aquifer	69,612 – 171,762	104,629	0.4-0.9%	0.6%
	Q/T Aquifer	43,235 – 134,828	86,108	0.2-0.7%	0.5%
	Mz/Pz Aquifer	298,470 – 595,195	408,050	1.6-3.2%	2.2%
	p€ Aquifer	352,492 – 810,169	450,302	1.9-4.4%	2.4%
	Absaroka Volcanics	1,347,874 – 3,084,193	1,749,295	7.3-16.7%	9.5%
	Low total	2,101,042	2,776,769	11.4-25.7%	15.0%
	High total	4,763,357			
WBRB	**Low total**	3,024,575	4,040,796	16.3-35.1%	21.8%
	High total	6,498,237			
WBRB less p€ & Volcanics	**Low total**	755,458	1,123,874	4.1-8.9%	6.1%
	High total	1,650,691			

[1] From **Table 6-8a,b** [2] WBRB total annual precipitation = 18,500,000 acre-feet (MWH et al., 2010)

easily treated as a storage volume 1,000 feet deep; where these units are exposed around the perimeters of the basins they are structurally complex **(Plates I and IV)**. In addition, recharge of the Mz/Pz Aquifer occurs mostly to the upturned strata of these hydrogeologic units, and percolation to the water-table occurs more parallel to bedding (direction of higher permeability) and may be greatly enhanced by fracture permeability. Therefore, recharge to the Mz/Pz Aquifer is generally higher and more effective than to the Q/T Aquifer (see **Table 6-7**), and there is greater tendency for fresh water recharge to flow to greater depth in the structural basin in some areas. An example of this is the Paleozoic Madison-Bighorn aquifer along the east side of the Bighorn Basin, where high-quality groundwater has been developed deep in prolific areas along anticlines that trend into the structural basins **(Appendix B)**. Lacking data for an alternate approach, and in spite of the well-known limitations, we used the evaluation of *aquifer-specific* recharge for supplementing the evaluation of basin-wide groundwater resources.

Recharge volumes were calculated using the following general equation:

Average annual recharge volume (ft^3)
= Outcrop area (ft^2) × average annual recharge (ft)

The areas of the exposed aquifers and groups of aquifers used for the recharge calculations **(Figures 6-2 through 6-6)** were determined from the hydrogeologic map **(Plate IV)** compiled for this study. Average annual rates of recharge in different areas of the WBRB are shown in **Figure 5-1,** as adapted

Table 6-10a. Recharge as percentage of stored and available groundwater, Q/T Aquifer [Shaded values: High and low estimates of recharge as a percentage of stored and of available groundwater in the Q/T Aquifer].

Basin		Stored groundwater						Available groundwater					
		Wind River Basin		Bighorn Basin		WBRB total		Wind River Basin		Bighorn Basin		WBRB total	
Sand / fine (%)		90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90
Groundwater volume (million acre-feet)		[1]535.0	[1]605.2	[1]573.0	[1]648.2	1,108.1	1,253.4	[2]22.7	[2]10.7	[2]24.3	[2]11.5	47.0	22.2
Recharge range (low/high, acre-ft)		Recharge as percentage of stored volume (%)						Recharge as percentage of available volume (%)					
Wind River Basin	87,254	0.016%	0.014%					0.38%	0.81%				
	261,030	0.049%	0.043%					1.2%	2.4%				
Bighorn Basin	43,235			0.008%	0.007%					0.18%	0.38%		
	134,828			0.024%	0.021%					0.56%	1.2%		
WBRB total	130,489					0.012%	0.010%					0.28%	0.59%
	395,858					0.036%	0.032%					0.84%	1.8%

[1] from Table 6-1 [2] from Table 6-3

Table 6-10b. Recharge as percentage of stored and available groundwater, Quaternary Aquifer 10-ft saturated thickness
[Shaded values: High estimates of recharge as a percentage of stored and of available groundwater in the Quaternary Aquifer, 10-ft thickness].

Basin		Stored groundwater						Available groundwater					
		Wind River Basin		Bighorn Basin		WBRB total		Wind River Basin		Bighorn Basin		WBRB total	
Sand / fine (%)		90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90
Groundwater volume (million acre-feet)		[1]2.98	[1]3.37	[1]3.26	[1]3.69	6.24	7.06	[2]2.38	[2]1.13	[2]2.61	[2]1.24	4.99	2.37
Recharge range (low/high, acre-ft)		Recharge as percentage of stored volume (%)						Recharge as percentage of available volume (%)					
Wind River Basin	[3]107,176	3.6%	3.2%					4.5%	9.5%				
	[3]293,090	9.8%	8.7%					12.3%	25.9%				
Bighorn Basin	[4]69,612			2.1%	1.9%					2.7%	5.6%		
	[4]171,762			5.3%	4.7%					0.56%	1.2%		
WBRB total	176,788					2.8%	2.5%					3.5%	7.4%
	464,852					7.4%	6.6%					9.3%	19.6%

[1] from Table 6-2ba [2] from Table 6-4a [3] from Table 6-8a [4] from Table 6-8b

Table 6-10c. Recharge as percentage of stored and available groundwater, Quaternary Aquifer 20-ft saturated thickness [Shaded values: Low estimates of recharge as a percentage of stored and of available groundwater, Quaternary Aquifer, 20-ft thickness].

Basin		Stored groundwater						Available groundwater					
		Wind River Basin		Bighorn Basin		WBRB total		Wind River Basin		Bighorn Basin		WBRB total	
Sand / fine (%)		90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90	90 / 10	10 / 90
Groundwater volume (million acre-feet)		[1]5.96	[1]6.74	[1]6.52	[1]7.38	12.5	14.1	[2]4.77	[2]2.27	[2]5.22	[2]2.48	9.99	4.75
Recharge range (low/high, acre-ft)		Recharge as percentage of stored volume (%)						Recharge as percentage of available volume (%)					
Wind River Basin	[3]107,176	1.8%	1.6%					2.2%	4.7%				
	[3]293,090	4.9%	4.3%					6.1%	12.9%				
Bighorn Basin	[4]69,612			1.1%	0.9%					1.3%	2.8%		
	[4]171,762			2.6%	2.3%					3.3%	6.9%		
WBRB total	176,788					1.4%	1.3%					1.8%	3.7%
	464,852					3.7%	3.3%					4.7%	9.8%

[1] from Table 6-2b [2] from Table 6-4b [3] from Table 6-8a [4] from Table 6-8b

from the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998). The recharge rates were grouped in five ranges over the WBRB. The recharge rates over the exposed areas of the aquifers were determined, the recharge rates were converted from inches to feet, and the average annual recharge volumes (in acre feet) were estimated using the general equation above.

Section 5.2 explained that some geologic units were not assignable to aquifers. For these recharge calculations, geologic unit areas clearly assigned to confining units were not considered; however, undifferentiated and undefined geologic units were included in the established *aquifer outcrop areas* of the Mz/Pz Aquifers to the extent that they were of the same Eras. The overall areas of the Absaroka Volcanics and p€ Aquifers were included in the recharge calculations without respect to their hydrogeologic assignments in **Plates II, III, and IV**, but rather on their overall physical characteristics and outcrop configuration.

The outer boundaries of the Q/T Aquifer areas were established a short distance basinward from the basal outcrop of the Tertiary interval to provide that the areas would have a 1000-foot thickness of relatively flat-lying Quaternary and Tertiary geologic units and to allow direct comparison between the contained volume and recharge estimates. The area composing the small gap between the outer Q/T Aquifer boundaries **(Figure 6-3)** and the outer edge of Tertiary geologic unit exposure **(Plate I)** was not included in the recharge calculations. Annual recharge calculations that exclude confining-unit outcrop areas provide a more conservative and perhaps more realistic estimate of available groundwater resources. Leakage from adjacent confining layers was not considered in this evaluation.

Tables 6-8a,b summarize calculated recharge for the Wind River and Bighorn basins over the ranges of average annual recharge mapped on **Figure 5-1** and the *outcrop areas* on **Figures 6-2 through 6-6.** A "best total" amount for each range of recharge over each *outcrop area* is also provided in **Tables 6-8a,b**. A "best total" is a weighted average calculated directly from the detailed (cell-by-cell) determinations. Recharge to the Quaternary Aquifer is included both in calculations for the Quaternary Aquifer alone and for the Q/T Aquifer within the interior basins – over the same areas used to calculate stored groundwater and available groundwater.

Table 6-9 recapitulates the estimated recharge range and "best total" recharge for the aquifers or groups of aquifers in the *outcrop areas* of each basin and gives the overall range and best total recharge for the WBRB and the percentage of these estimated volumes with respect to total annual precipitation in the WBRB. **Table 6-9** shows that the p€ Aquifer in both basins and the Absaroka Volcanics in the Bighorn Basin stand out as receiving more recharge than the other outcrop areas. In addition, the Bighorn Basin accounts for slightly more than twice the recharge of the Wind River Basin, largely because of the large area covered by the Absaroka Volcanics in the Bighorn Basin. When all recharge estimated for the WBRB is considered, it constitutes a substantial percentage of total precipitation (16 percent to 35 percent), higher than allowed in consideration of surface water outflows, consumptive uses, and evapotranspiration estimates in the water resources mass balance of MWH et al. (2010) – and discussed in detail in **Chapter 8**. However, as discussed previously, when recharge to the Precambrian and volcanic terrains is discounted, because much of the recharge to these areas is discharged to surface waters, total recharge as a percentage of total precipitation (4 percent to 9 percent) is more in line with convention (10 percent). To the extent that recharge is rejected from other aquifers, especially the Paleozoic carbonate aquifers, where it can be evaporated, used, and included in surface flows, the volume of water going into subsurface storage (and recharge as a term in the water resources mass balance) is reduced.

The high rate of recharge over the high-elevation Precambrian outcrop areas does not translate into large quantities of groundwater stored in the Precambrian aquifers. Groundwater in the p€ Aquifer is limited to relatively shallow fractures that are adequately porous to contain significant groundwater, typically to depths of less than 300 feet below the lowest elevation of erosion along drainages. Most groundwater in the p€ Aquifer discharges to lakes and flows in mountain streams. Groundwater flow that does not discharge before it becomes covered by sedimentary geologic units will recharge these overlying strata before it migrates very far into the structural groundwater basin. The high rate of recharge to the p€ Aquifer is generally balanced by a high rate of natural discharge. Groundwater resources of the p€ Aquifer in the WBRB are limited to local springs and low-yield wells.
Recharge calculated by Hamerlinck and Arneson (1998) for the large mountainous area covered by the Absaroka Volcanics (exclusive of Yellowstone Park) is also very high; however, many of the geologic units that crop out in this area have not been defined as hydrogeologic units **(Plates IV** and **V)**. The rocks within the Absaroka volcanic terrain are in very complex to chaotic stratigraphic configuration (Sundell, 1993); and because the area is extremely rugged and largely within the National Forest system, very little subsurface data exists. Accordingly, the groundwater resources in this area have not been studied and are not clearly defined. It is assumed that because of the complex and chaotic geology and the deep erosion of the area, most recharge is quickly discharged to lakes, streams, and wetlands, and that groundwater retained in the volcanic rocks generally is perched within discontinuous local aquifers.

Tables 6-10a,b,c compare recharge rates with stored and

available groundwater volumes for the Q/T Aquifer in the interior basin areas and for the Quaternary Aquifer basin-wide. Comparisons are made for each basin and for the total WBRB over the same high and low ends of the ranges of "sand" and "fine" lithologies used for the stored and available volume calculations **(Tables 6-5** and **6-6a,b)**.

The thickness over which the enormous volumes of stored and available groundwater were calculated for the Q/T Aquifer. Annual recharge is a fairly low percentage of both stored and available groundwater. Predictably, recharge is a lower percentage of stored than of available groundwater, as available groundwater is between approximately 2 and 4 percent of stored groundwater **(Table 6-5)**. For the overall WBRB, recharge as a fraction of stored groundwater ranges from 0.10 percent (for 10/90 sand/fine lithology and low recharge) to 0.036 percent (for 90/10 sand/fine lithology and high recharge). For the overall WBRB, recharge as a fraction of available groundwater ranges from 0.28 percent (for 90/10 sand/fine lithology and low recharge) to 1.8 percent (for 10/90 sand/fine lithology and high recharge) [values shaded in **Table 6-10a**]. In general, recharge as a percentage of both stored and available groundwater is approximately twice as high for the Q/T Aquifer in the Wind River Basin as in the Bighorn Basin. This is probably because of the larger areas receiving from one to ten inches of annual recharge in the Wind River Basin, primarily over the Quaternary Aquifer **(Figure 5-1)**. On the basis of the criteria of Hamerlinck and Arneson (1998), the higher recharge in the Wind River Basin appears to be due to more favorable soil/vegetation conditions.

Because of the substantially thinner saturated intervals (10 and 20 feet) assumed for calculating total and available groundwater volumes in the Quaternary Aquifer, annual recharge to the Quaternary Aquifer constitutes a substantially higher percentage of both stored and available groundwater than recharge to the Q/T Aquifer. Similarly to the Q/T Aquifer value, recharge is a slightly lower percentage of stored than of available groundwater, as available groundwater ranges from approximately 34 percent to 80 percent of the stored volume **(Table 6-6a,b)**. For the overall WBRB Quaternary Aquifer, recharge as a fraction of stored groundwater ranges from 1.3 percent (for 20-foot saturated thickness, 10/90 sand/fine lithology, low recharge; **Table 6-10c**) to 7.4 percent (for 10-foot saturated thickness, 90/10 sand/fine lithology, high recharge; **Table 6-10b**). For the overall WBRB, recharge as a fraction of available groundwater ranges from 1.8 percent (for 20-foot saturated thickness, 90/10 sand/fine lithology, low recharge; **Table 6-10c**) to 19.6 percent (for 10-foot saturated thickness, 10/90 sand/fine lithology, high recharge; **Table 6-10b**) [values shaded in **Figure 6-10b,c**]. Also similarly to the Q/T Aquifer value, recharge as a percentage of both stored and available groundwater is higher in the Wind River Basin than in the Bighorn Basin because a larger area of the Quaternary Aquifer receives from one to ten inches of annual recharge **(Figures 5-1, 6-2)** in the Wind River Basin, apparently due to more favorable soil/vegetation conditions.

6.2.3 Summary

- Recharge ultimately controls the availability and sustainability of regional groundwater resources. Recharge is primarily controlled both directly and indirectly by precipitation. Total average annual precipitation for the WBRB has been reported as 18,500,000 acre-feet (MWH et al., 2010a).
- Average annual recharge has been estimated by Hamerlinck and Arneson (1998) as ranging from 0 to 55 inches, with the lowest values in the interior basins and the highest in the surrounding mountain ranges, as controlled by precipitation and soil/vegetation combinations.
- The recharge efficiency (recharge as a percentage of precipitation, R/P) varies on the basis of factors used by Hamerlinck and Arneson to estimate recharge throughout Wyoming.
- Other factors also control recharge and may dominate locally (e.g., solution enhanced fractures). However, overall these factors should confirm the pattern of recharge and recharge efficiency based on Hamerlinck and Arneson.
- Recharge (from precipitation) to the flat-lying Q/T Aquifer in the interior basin areas is generally less efficient than to the upturned sedimentary Mz/Pz Aquifer in the surrounding upland and mountainous areas. Recharge is more efficient in some areas of the Quaternary Aquifer in the interior Wind River basin, probably due to favorable soil/vegetation combinations.
- Recharge in the WBRB is most efficient in the high mountain p€ crystalline and Absaroka volcanic terrains; however, much of the groundwater flow in these aquifers is rejected and discharged to surface waters.
- Estimates of average annual recharge to *aquifer outcrop areas* (Quaternary Aquifer, Q/T Aquifer, Mz/Pz Aquifer, p€ Aquifer, Absaroka Volcanics) based on the recharge rates of Hamerlinck and Arneson are calculated separately for the Wind River and Bighorn Basins. Each estimate is presented as a high/low range consistent with the range of recharge rates mapped over the aquifer outcrop areas and as a "best total" based on the cell-by-cell product of area and recharge rate.
- While the total annual recharge estimate constitutes a substantial fraction (16 to 35 percent) of total annual precipitation for the WBRB, deducting recharge to the p€ Aquifer and Absaroka Volcanics (because much of this groundwater flow is discharged to

surface waters) brings the resulting recharge efficiency (6 percent) more in line with convention (10 percent).

- For the WBRB, total average annual recharge as a fraction of total stored and available groundwater in the Q/T Aquifer is predictably a much smaller percentage than in the Quaternary Aquifer. This is primarily because of the great difference in volume between the two aquifers, but also because in the Wind River Basin, soil/vegetation combinations developed on alluvial deposits are more favorable to recharge.
- In some areas of the Quaternary Aquifer in the Wind River Basin, estimated recharge is a substantial percentage of both stored and available groundwater. This suggests that the resource in these areas may be sustainable at close to the estimated (natural) recharge. Recharge from irrigation in these areas would add to the groundwater resource.
- A more comprehensive analysis of recharge using the additional factors discussed in **Sections 5.1.3.1 and 5.4,** especially for the Mz/Pz Aquifer, would provide a more comprehensive understanding of WBRB groundwater resources.

Chapter 7

WBRB Hydrogeologic Units – Physical and Chemical Characteristics

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For this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are summarized in tabular format **(Plate IX)**. 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 yields, 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 made 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.

The discriptions below of groundwater chemical characteristics are introduced in detail in **Section 5.6.1**. **Figure 7-1** shows the water-quality sample locations in the WBRB.

7.1 Wind River Basin

The physical and chemical characteristics of hydrogeologic units in the Wind River Basin (WRB) are described in this section of the report. Hydrogeologic units of the WRB are identified in **Plate II**.

7.1.1 Quaternary unconsolidated-deposit aquifers

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

Physical characteristics

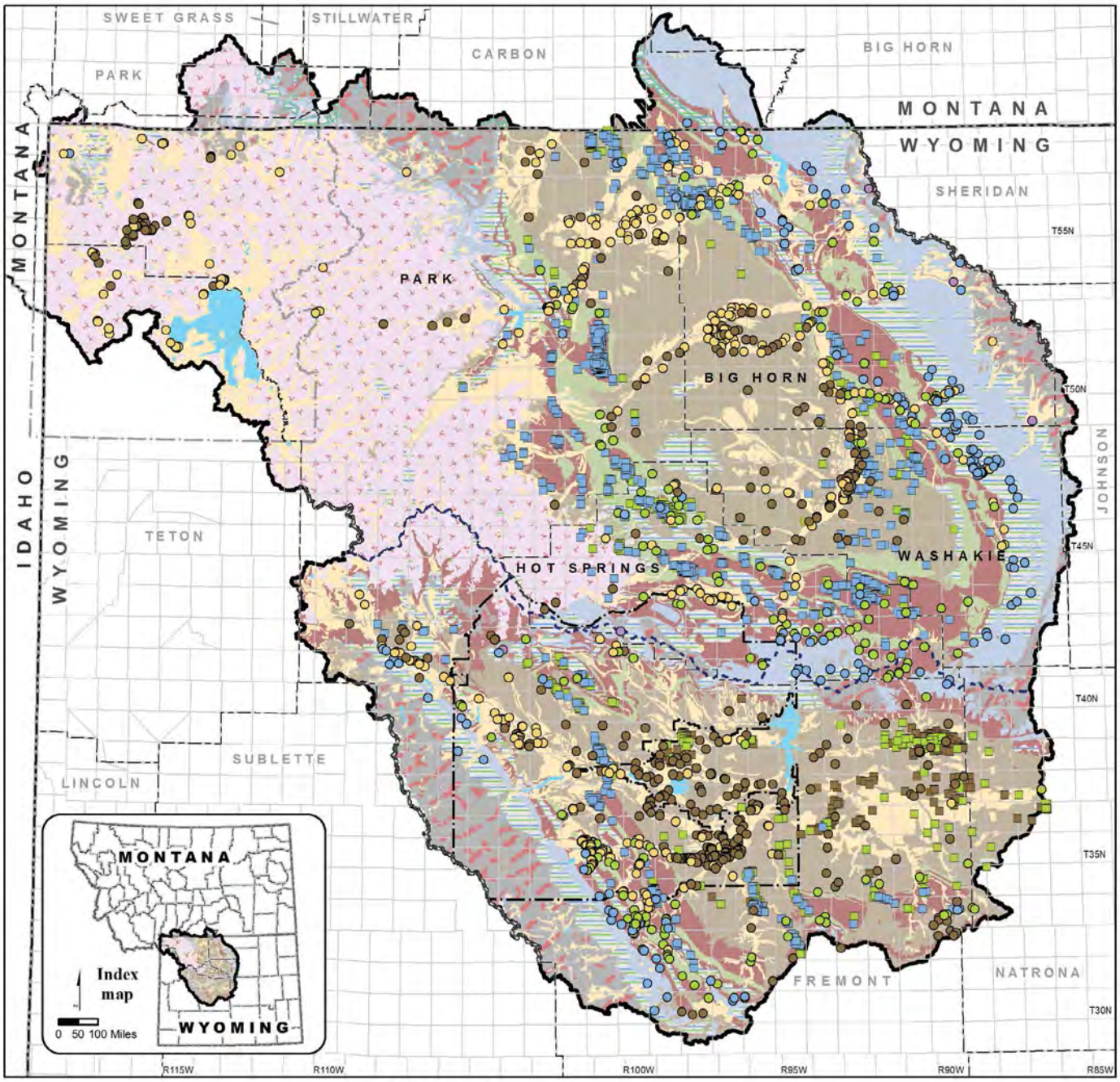
Unconsolidated deposits of Quaternary age contain aquifers (referred to herein as "Quaternary unconsolidated-deposit aquifers") that can be highly productive locally and are the source of water for many shallow wells in the WRB. In the WRB, Quaternary unconsolidated-deposit aquifers are used as sources of water for domestic, stock, or public-supply purposes.

Quaternary-age 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 (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Nelson Engineering, 1992; Jorgensen Engineering and Land Surveying, 1993a,b; Plafcan et al., 1995; Daddow, 1996; Stetson Engineering, Inc., 2004, 2007a,b). Alluvium along the Wind River or in tributary-stream valleys that drain the Wind River Range generally is coarse-grained, whereas alluvium along the southeast valleys of Beaver Creek and Kirby Draw, and in the center of the basin along the valleys of Fivemile, Muddy, and Cottonwood Creeks, is generally fine-grained (McGreevy et al., 1969). Groundwater in Quaternary unconsolidated-deposit aquifers typically is unconfined (water-table conditions predominate). Quaternary unconsolidated-deposit aquifers are small in area and occur primarily in alluvium (commonly associated with colluvium and referred to as "alluvial aquifers") or terrace deposits (referred to as "gravel, pediment, and sand deposits" in some reports and herein as "terrace-deposit aquifers") along narrow valleys and in adjacent upland areas, and along streams and rivers in the WRB **(Plate I)**. Consequently, many wells completed in Quaternary unconsolidated-deposit aquifers are located close to and along streams and rivers. Along the floodplains, wells completed in alluvium likely are in hydraulic connection with streams and rivers. In places, Quaternary unconsolidated-deposit aquifers may be composed of saturated glacial deposits [for example, Dinwoody Lakes and Bull Lake area (Daddow, 1996) and Dubois area (Stetson Engineering, Inc., 2007b)] or of saturated landslide and dune sand (eolian) deposits (Whitcomb and Lowry, 1968; McGreevy et al., 1969). Terrace deposits may be present in many different terrace levels alongside rivers draining the basin and in adjacent upland areas (for example, Morris et al., 1959, p. 27-31).

The thickness of an alluvial or terrace deposit in the WRB depends on stream or river valley association and location. Some Quaternary-age unconsolidated deposits are as much as 200 feet (ft) thick (Richter, 1981), but the thickness of most Quaternary-age unconsolidated deposits is less than 50 ft (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Nelson Engineering, 1992; Jorgenson Engineering and Land Surveying, 1993b; Plafcan et al., 1995; Daddow, 1996; Stetson Engineering, Inc., 2004, 2007b).

Well yields in Quaternary unconsolidated-deposit aquifers in the WRB **(Plate IX)** are directly related to the size and sorting of materials composing the deposits, as well as the saturated thickness of the deposits. In places, well yields are high because of large saturated thickness and very coarse deposits. Hydrogeologic data describing the Quaternary unconsolidated-deposit aquifers in the WRB (alluvial aquifers, terrace-deposit aquifers, aquifers in landslide deposits, aquifers in dune sand (eolian) deposits, and glacial-deposit aquifers), including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate IX**.

The areal extent of Quaternary unconsolidated-deposit aquifers coincides with much of the rural population and irrigated cropland in the WRB, making these aquifers particularly susceptible to contamination from human activities. Evidence of groundwater contamination by human activities in the WRB has been indicated by detection of elevated nitrate concentrations, as well as by detection of organic compounds such as volatile organic compounds and pesticides (Plafcan et al., 1995; Daddow, 1996; Eddy-Miller and Norris, 2000b, 2001; Eddy-Miller and Remley, 2005; Bartos et al., 2008, 2009).



Explanation

(See Figure 3-1 for explanation of additional symbols)

Environmental groundwater sample location

- Quaternary
- Cenozoic
- Mesozoic
- Paleozoic
- Precambrian

Produced groundwater sample location

- Cenozoic
- Mesozoic
- Paleozoic

- Hydrologic divide between the Wind and Bighorn river basins
- Yellowstone National Park boundary
- Wind River Indian Reservation boundary

Hydrogeologic unit

- Ice
- Water
- Quaternary aquifers
- Absaroka – Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

0 5 10 20 30 Miles

N

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Source:

U.S. Geological Survey

Figure 7-1. Groundwater quality sample locations, Wind/Bighorn River Basin.

Recharge, discharge, and groundwater movement

Recharge to many Quaternary unconsolidated-deposit aquifers is not only from direct infiltration of precipitation and ephemeral and perennial streamflow losses, but also from infiltration of diverted surface water through unlined irrigation canals and ditches – from water applied to fields – and discharge from underlying aquifers (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Nelson Engineering, 1992; Jorgensen Engineering and Land Surveying, 1993b; Plafcan et al., 1995; Daddow, 1996; James Gores and Associates, 1999a,b; Stetson Engineering, Inc., 2004, 2007b). Recharge to alluvial aquifers is primarily from streams and irrigation; and water levels in alluvial aquifers vary seasonally with streamflow (Morris et al., 1959; McGreevy et al., 1969; Richter, 1981). Morris et al reported that Muddy Creek was a losing stream within the Riverton Irrigation Project during September 1949, with streamflow losses of 113 cubic feet per second. In many locations in the WRB, unconsolidated terrace deposits were not saturated prior to irrigation, indicating that recharge of diverted surface water likely is the dominant source of recharge to these terrace-deposit aquifers (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969). Water levels in many terrace-deposit aquifers are directly related to irrigation diversions. During the irrigation season, water levels in some of these deposits are sometimes at the same elevation as water levels in unlined irrigation canals and ditches (Morris et al., 1959). Water levels in terrace-deposit aquifers typically begin to rise after irrigation begins and gradually decrease after irrigation ceases (for example, Morris et al., 1959, Figures 7 and 8). Water levels in terrace-deposit aquifers are highly variable and dependent on seasonal recharge, and some wells completed in the terrace deposits "dry up" in the late summer and early fall (Richter, 1981, p. 87).

Discharge from Quaternary unconsolidated-deposit aquifers occurs by evapotranspiration, gaining streams, seeps, drains, spring flows, and withdrawals from wells (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Nelson Engineering, 1992; Jorgensen Engineering and Land Surveying, 1993b; Plafcan et al., 1995; Daddow, 1996). Evapotranspiration from Quaternary unconsolidated-deposit aquifers is likely to be highest in areas where crops are grown.

The direction of groundwater flow in most Quaternary unconsolidated-deposit aquifers is generally the same as the slope of the land surface, although underlying bedrock surface irregularities locally alter the direction of movement (Morris et al., 1959). In alluvial aquifers, the direction of groundwater flow generally is toward a river or in the direction of streamflow; this includes underflow parallel to streamflow. In terrace-deposit aquifers, the direction of groundwater flow generally is toward the principal surface drainage. Groundwater flow in Quaternary unconsolidated-deposit aquifers (alluvium and colluvium) in the Midvale area of the Riverton irrigation project is shown on a water-table contour map representing the water table before and during the latter part of the 1950 irrigation season (Morris et al., 1959, Plate 2). Daddow (1996) constructed three water-table contour maps for Quaternary unconsolidated-deposit aquifers located on the Wind River Indian Reservation. Water-table contours (reproduced in **Figures 7-2, 7-3, and 7-4**) show the direction of groundwater flow in these areas, and show that many of the perennial stream reaches were gaining when water levels were measured. Daddow (1996, p. 19) noted that "groundwater movement in the Crowheart area generally is a subdued reflection of the slope of the land surface." Daddow (1996, p. 19) included floodplain alluvium of Meadow Creek in the water-table contour map of the Crowheart area "because it is topographically similar to the adjacent terrace deposits and assumed to be hydraulically connected to the water table in the adjacent terrace deposits," whereas floodplain alluvium of Willow Creek was excluded "because the floodplain alluvium of the stream is substantially entrenched and separated from the terrace deposits by outcrops of the Wind River Formation" **(Figure 7-3)**.

Chemical characteristics

The chemical characteristics of groundwater from alluvial aquifers, terrace-deposit aquifers, aquifers in landslide deposits, aquifers in dune sand (eolian) deposits, and glacial-deposit aquifers in the WRB are evaluated in this section of the report.

Alluvial aquifers

The chemical composition of groundwater in alluvial aquifers in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 122 wells and one spring. Summary statistics calculated for available constituents are listed in Appendix E1, and major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G1, diagram A). TDS concentrations were variable and indicated that most waters were fresh (72 percent of samples) and remaining waters ranged from slightly to moderately saline (Appendix E1; Appendix G1, diagram A; supplementary data tables). TDS concentrations ranged from 102 to 4,630 mg/L, with a median of 539 mg/L.

Concentrations of some properties and constituents in water from alluvial aquifers in the WRB 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 (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent exceeded the proposed MCL, whereas 20 percent exceeded the alternative MCL), boron (2 percent), nitrate plus nitrite (2 percent), and nitrate (2 percent).

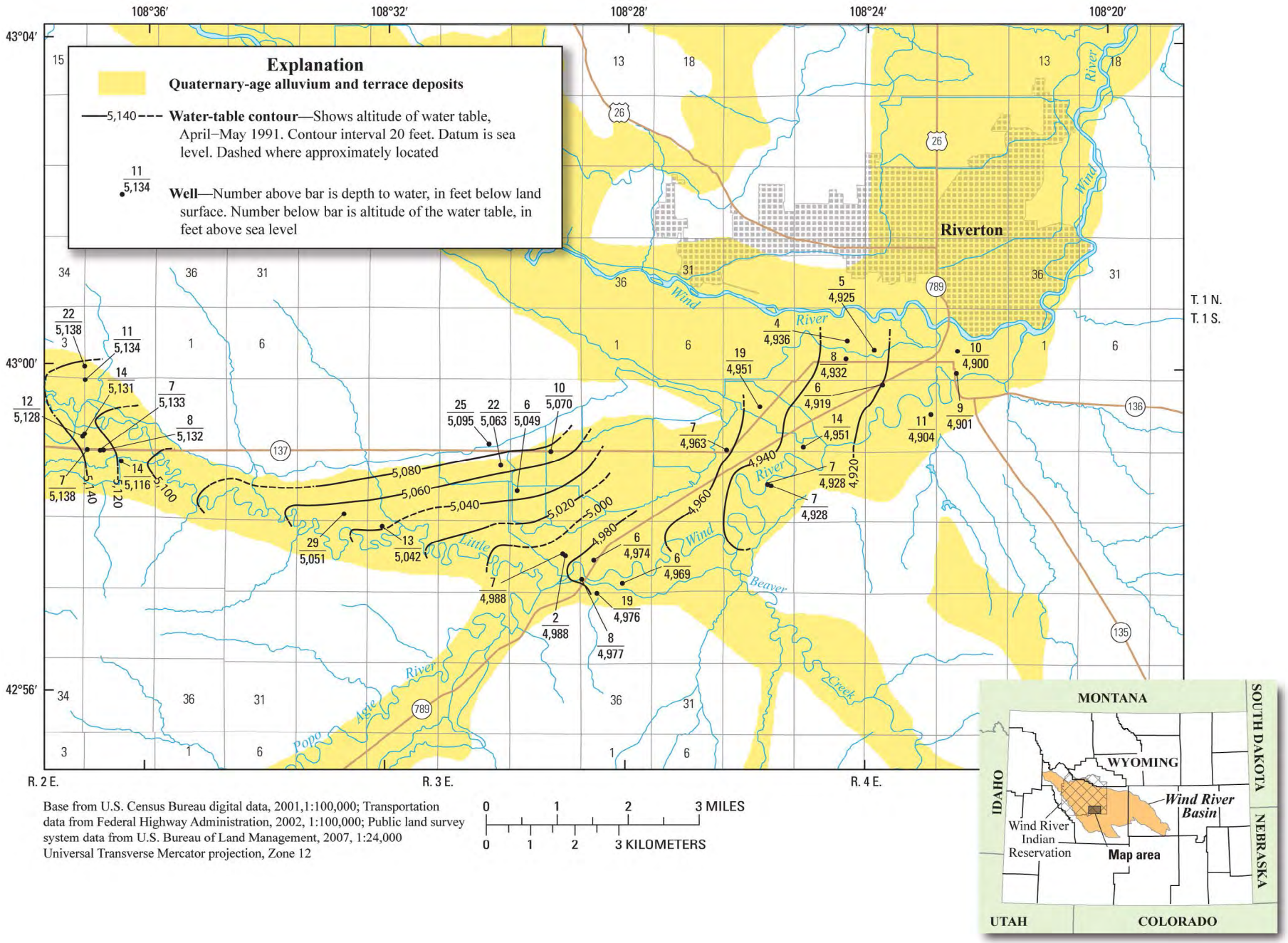
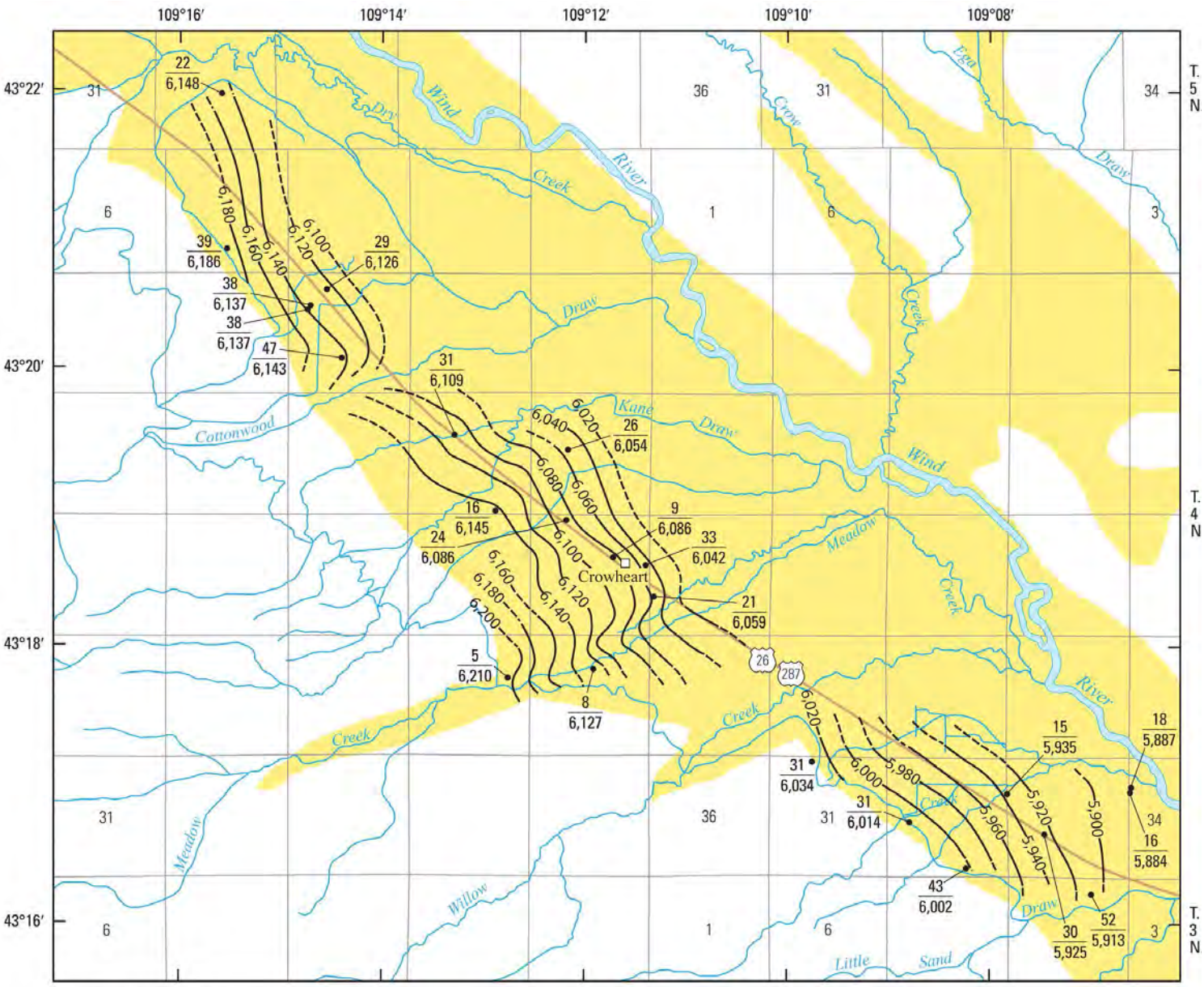


Figure 7-2. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the lower Little Wind River Basin, Wyoming (modified from Daddow, 1996, Plate II).



Base from U.S. Census Bureau digital data, 2001,1:100,000; Transportation data from Federal Highway Administration, 2002, 1:100,000; Public land survey system data from U.S. Bureau of Land Management, 2007, 1:24,000
Universal Transverse Mercator projection, Zone 12

0 1 2 MILES
0 1 2 KILOMETERS

Explanation

Quaternary-age alluvium and terrace deposits

—6,200– – – **Water-table contour**—Shows altitude of water table, May 1991. Contour interval 20 feet. Datum is sea level. Dashed where approximately located

5 / 6,210 **Well**—Number above bar is depth to water, in feet below land surface. Number below bar is altitude of the water table, in feet above sea level

Figure 7-3. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the Crowheart area of the Wind River Indian Reservation, Wyoming (modified from Daddow, 1996, Plate III).

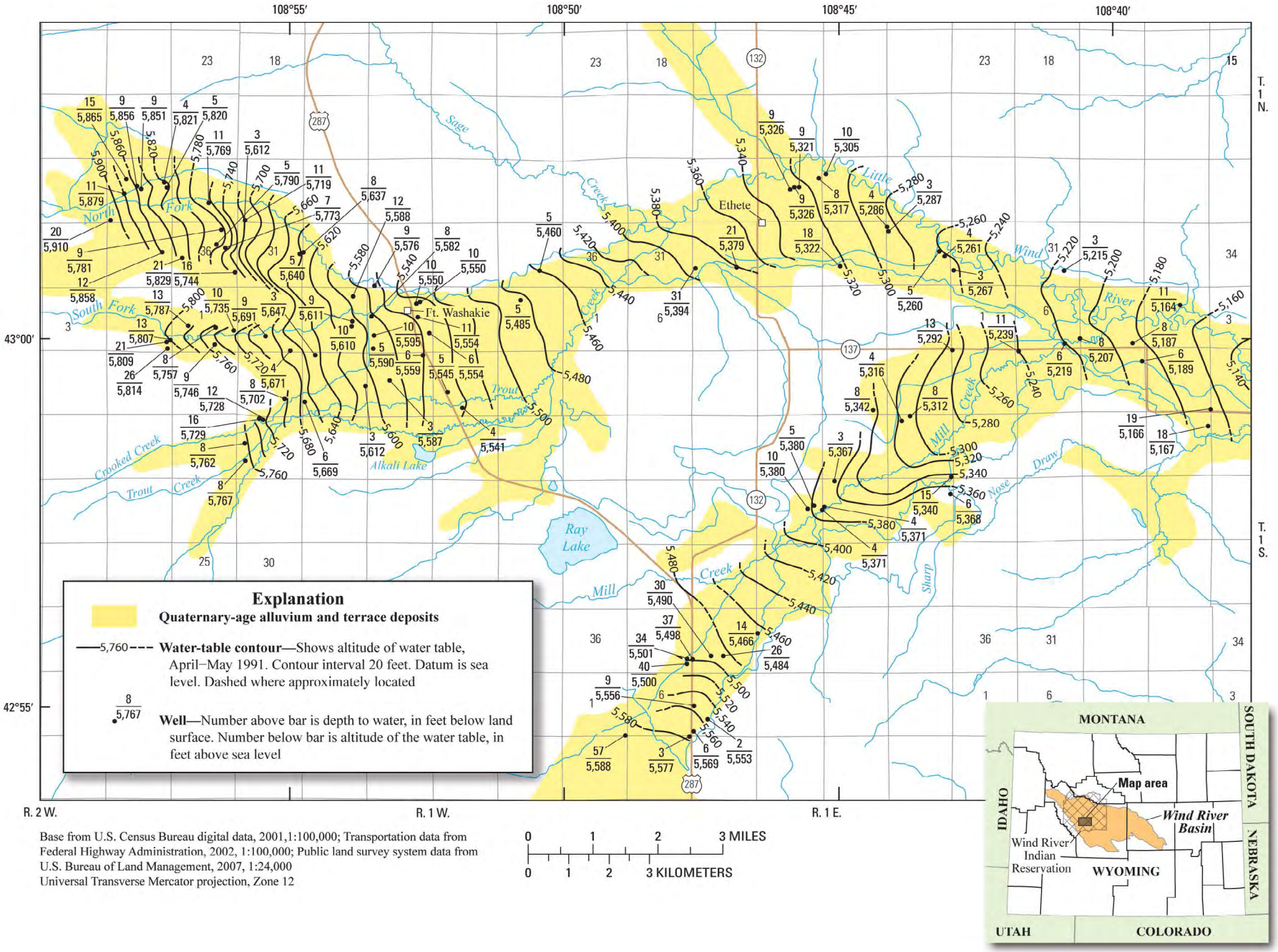


Figure 7-4. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the upper Little Wind River and Mill Creek Basins, Wyoming (modified from Daddow, 1996, Plate II).

Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (54 percent), sulfate (42 percent), manganese (36 percent), filtered iron (28 percent), pH (2 percent above upper limit), and chloride (2 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (47 percent), manganese (17 percent), TDS (9 percent), SAR (4 percent), boron (4 percent), chloride (4 percent), pH (2 percent above upper limit), and filtered iron (2 percent). Properties and constituents measured at concentrations greater than livestock-use standards were pH (2 percent above upper limit) and boron (2 percent).

Terrace-deposit aquifers

The chemical composition of groundwater in terrace-deposit aquifers in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 18 wells. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram B**). TDS concentrations were variable and indicated that most waters were fresh (62 percent of samples) and remaining waters were slightly to moderately saline (Appendix E1; Appendix G1, diagram B; supplementary data tables). TDS concentrations ranged from 85 to 4,400 mg/L, with a median of 746 mg/L.

Concentrations of some properties and constituents in water from terrace-deposit aquifers in the WRB 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 (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent) and fluoride (7 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (69 percent), sulfate (44 percent), manganese (17 percent), filtered iron (10 percent), fluoride (7 percent), and pH (6 percent below lower limit and 6 percent above upper limit).

Concentrations of some properties and constituents in water from terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (44 percent), TDS (12 percent), and SAR (8 percent). One property (pH) had values outside the range for livestock-use standards (6 percent below lower limit and 6 percent above upper limit).

Aquifers in landslide deposits

The chemical composition of groundwater in aquifers in landslide deposits in the WRB was characterized and the quality evaluated on the basis of one environmental water sample from a spring. Individual constituent concentrations are listed in **Appendix E1**.

The TDS concentration (154 mg/L) indicates that the water was fresh. On the basis of the properties and constituents analyzed, the quality of water from aquifers in landslide deposits in the WRB was suitable for most uses. No properties or constituents in water from the landslide deposits had concentrations that approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Aquifers in dune sand (eolian) deposits

The chemical composition of groundwater in aquifers in dune sand (eolian) deposits in the WRB was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (833 mg/L) indicates that the water was fresh.

Concentrations of some properties and constituents in water from dune sand (eolian) deposits in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. In comparison with health-based standards (USEPA MCLs and HALs), only ammonia was measured at a concentration exceeding domestic-use standards. TDS and sulfate concentrations exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of SAR and sulfate in water from dune sand (eolian) deposits exceeded State of Wyoming agricultural-use standards. No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

Glacial-deposit aquifers

The chemical composition of groundwater in the glacial-deposit aquifers in the WRB was characterized and the quality evaluated on the basis of environmental water samples from four wells. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations indicated that all waters were fresh (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 108 to 306 mg/L, with a median of 246 mg/L.

On the basis of the properties and constituents analyzed for, the quality of water from glacial-deposit aquifers in the WRB was suitable for most uses. No properties or constituents in water from the glacial-deposit aquifers had concentrations that approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.1.2 Split Rock aquifer

The Oligocene and Miocene-age Split Rock Formation composes the Split Rock aquifer in the WRB **(Plate II)**. The Split Rock aquifer is present only in the southeastern WRB; most of the areal extent is in the Granite Mountains area outside the Wind River-Bighorn Basin Plan study area **(Plate I)**. Rocks composing the Split Rock Formation were originally assigned to the Split Rock Formation by Love (1961), were renamed the Arikaree Formation (see Denson, 1965; Whitcomb and Lowry, 1968; Denson and Pipiringos, 1974; Richter, 1981), were mapped as Miocene-age rocks on the State geologic map (Love and Christiansen, 1985), and were again defined as the Split Rock Formation in the State Stratigraphic Nomenclature Chart (Love et al., 1993). The Split Rock Formation is composed of fine- to medium-grained sandstone with some beds of tuff; conglomerate is present in the upper and lower parts of the formation (Denson, 1965; Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein; Love et al., 1993). The reported thickness of the Split Rock Formation ranges from 0 to 930 ft (Richter, 1981, table IV-1). Groundwater in the Split Rock aquifer is unconfined in most areas, but is semi-confined in some areas (Whitcomb and Lowry, 1968; Richter, 1981). Whitcomb and Lowry (1968, p. 3) reported that well yields "differ greatly, depending on the permeability of the water-bearing material, the depth of penetration, and well construction," and also noted that fractures may increase aquifer permeability in some areas. Richter (1981, table IV-1) reported that the aquifer was highly permeable and productive in the WRB and had "good intergranular permeability and porosity." Most wells completed in the aquifer are used for stock watering (Plafcan et al., 1995). Regional groundwater flow in the aquifer is eastward and toward the Sweetwater River and tributary canyons (Richter, 1981). Numerous perched springs discharge small quantities of water [generally less than 20 gallons per minute (gal/min)] from the aquifer, most commonly along bedding plane partings (Richter, 1981). No water-quality or hydrogeologic data are available for the Split Rock aquifer in the study area.

7.1.3 White River aquifer

The physical and chemical characteristics of the White River aquifer in the WRB are described in this section of the report.

Physical characteristics

The Oligocene-age White River Formation composes the White River aquifer in the WRB **(Plate II)**. The White River Formation is composed of fine-grained sandstone with interbedded beds of tuff and bentonite, and discontinuous lenses of arkose and conglomerate (Van Houten, 1964; Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein). Reported thickness of the White River Formation ranges from 0 to 650 ft (Van Houten, 1964). The White River aquifer has very small areal extent and is present only in the southeastern WRB **(Plate I)**. Groundwater in the aquifer is likely unconfined or semi-confined (Richter, 1981). Richter (1981, table IV-1) reported that the aquifer was highly permeable and productive in the WRB and had "good intergranular permeability and porosity," but few data were located during the present study to corroborate this interpretation. Sparse hydrogeologic data are available for the White River aquifer; the available spring-discharge measurements are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the White River aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from one well and five springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations indicated that waters were fresh (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 247 to 823 mg/L, with a median of 334 mg/L.

Concentrations of some properties and constituents in water from the White River aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (25 percent of samples analyzed for the property) and sulfate (25 percent).

Concentrations of one constituent exceeded State of Wyoming agricultural-use standards and no concentrations of properties and constituents exceeded State of Wyoming livestock standards in the WRB. The constituent in environmental water samples measured at concentrations greater than agricultural-use standards was sulfate (25 percent).

7.1.4 Aycross–Wagon Bed confining unit

The physical and chemical characteristics of the Aycross–Wagon Bed confining unit in the WRB are described in this section of the report.

Physical characteristics

The upper and middle Eocene-age Tepee Trail, Aycross, and Wagon Bed Formations compose the Aycross–Wagon Bed

confining unit in the WRB **(Plate II)**. The Tepee Trail and Aycross Formations have very small areal extent and are present only in the northwestern WRB **(Plate I)**; these formations generally consist of volcaniclastic sandstone, conglomerate, mudstone, shale, tuff, and lava flows (Love, 1939; Keefer, 1957; Richter, 1981, and references therein; Bown, 1982). Where present, the Tepee Trail and Aycross Formations overlie the Wind River Formation **(Plate II)**. Reported thickness of the Tepee Trail Formation ranges from 0 to about 2,000 ft, whereas reported thickness of the Aycross Formation ranges from 0 to about 1,000 ft (Love, 1939; Bown, 1982). The Wagon Bed Formation is composed of tuffaceous, bentonitic sandstone, siltstone, and mudstone, and ranges from 0 to 700 ft in thickness (Van Houten, 1964). The Wagon Bed Formation has very small areal extent and is present only in the southeastern WRB **(Plate I)**. Although considered part of the Aycross–Wagon Bed confining unit, both the Tepee Trail and Wagon Bed Formations may yield small quantities (less than 10 gal/min) of water to springs and shallow wells along outcrop areas (Whitcomb and Lowry, 1968; Richter, 1981, table IV-1). Hydrogeologic data for the Tepee Trail and Aycross Formations are not available, but sparse data describing well-yield and spring-discharge measurements from the Wagon Bed Formation are summarized in **Plate IX** for the Aycross–Wagon Bed confining unit.

Chemical characteristics

No groundwater-quality samples were available from the Tepee Trail and Aycross formations. The chemical composition of groundwater for the Aycross–Wagon Bed confining unit was characterized and the quality evaluated on the basis of environmental water samples from two wells completed in, and two springs discharging from, the Wagon Bed Formation in the WRB. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations indicated that waters were fresh (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 207 to 572 mg/L, with a median of 282 mg/L.

Concentrations of few properties and constituents in water from the Aycross–Wagon Bed confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (25 percent). No properties or constituents had concentrations that approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.1.5 Wind River aquifer

The physical and chemical characteristics of the Wind River aquifer in the WRB are described in this section of the report.

Physical characteristics

The Wind River aquifer is a major aquifer in the WRB. Many wells are installed in the Wind River aquifer because it is present at or near land surface (crops out) throughout most of the Wind River Basin **(Plate I)**. The aquifer is used as a source of water for domestic, stock, irrigation, industrial, and public-supply purposes throughout the WRB (Libra et al., 1981; Daddow, 1996). The aquifer is an important public-water supply source for the city of Riverton and surrounding area (Anderson and Kelly, Inc., 1976; James Gores and Associates, 1998a,b; Keller Associates, 2008a,b); in fact, Anderson and Kelly, Inc. considered the Wind River aquifer to be the sole source of groundwater in the Riverton area.

The Eocene-age Wind River Formation composes the Wind River aquifer in the WRB **(Plate II)**. Thickness of the Wind River Formation ranges from about 100 ft along mountain flanks to about 5,000 ft in the central basin (Daddow, 1996). The Wind River Formation is composed of an interbedded sequence of claystone, shale, siltstone, and conglomerate, with lenticular beds of fine- to coarse-grained sandstone of variable thickness and areal extent; small amounts of bentonite, tuff, and limestone also may be present (Morris et al., 1959; McGreevy et al., 1969). Coarse deposits may be most abundant along the basin margins because of proximity to sediment sources such as the Wind River and Washakie Ranges and the Owl Creek Mountains (Whitcomb and Lowry, 1968).

The Wind River Formation is underlain by the Indian Meadows Formation or by the Fort Union Formation in the absence of the Indian Meadows Formation **(Plate II)**. In the Wind River Range, the Wind River Formation may be underlain by the conglomerate of Roaring Fork **(Plate II)**. Where buried in the WRB, the Wind River Formation is overlain by the Aycross-Wagon Bed confining unit [composed of the volcaniclastic Tepee Trail and Aycross formations or siliciclastic Wagon Bed Formation **(Plate II)**], or Quaternary-age unconsolidated deposits **(Plate II)**. Most wells completed in the Wind River aquifer are for stock and domestic use because of relatively low yields and water quality that may preclude some uses without treatment (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Libra et al., 1981; Daddow, 1996).

McGreevy et al. (1969) qualitatively divided the Wind River Formation on the Wind River Indian Reservation into three distinct sequences (facies) – (1) a several-thousand-foot-thick lower fine-grained sequence composed of brown, maroon, red, and gray siltstone and shale with predominantly fine-grained sandstone; (2) an approximately 1,000-ft thick middle coarse-grained sequence composed of green and gray, coarse-grained arkosic sandstone, conglomerate, and siltstone; and (3) an upper

facies (present in the eastern part of the reservation) as much as 800 ft thick composed of gray and green siltstone, shale, and fine-grained sandstone with thin beds of red, maroon, and green siltstone and shale. McGreevy et al. (1969, p. I44) noted that the middle coarse-grained sequence intertongues with and underlies the upper fine-grained sequence, and that "many of the coarse-grained sandstone and conglomerate beds are very well sorted, loosely cemented, and very porous."

The lenticular sandstone beds and conglomerates vary widely in geometry and thickness, and are the permeable units in the formation that readily yield water to wells and compose the aquifer (Morris et al., 1959; McGreevy et al., 1969). The lenticular sandstone beds have different transmissivities and different degrees of hydraulic interconnection, and can be considered individual aquifers at local scale (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969). Sandstone beds may be unconfined (water-table conditions) or confined (Morris et al., 1959; McGreevy et al., 1969; Daddow, 1996), but Daddow noted that wells greater than 100 ft deep on the Wind River Indian Reservation generally yielded groundwater from confined sandstone beds, whereas shallower wells generally yielded groundwater from unconfined sandstone beds. Detailed studies of the middle coarse-grained sequence in the Riverton area indicate that few sandstone beds can be correlated very far, as most are lenticular, discontinuous, and separated by less permeable fine-grained rocks such as shale and siltstone (Anderson and Kelly, Inc., 1976; James Gores and Associates, 1998b). Consequently, the fine-grained rocks can hydraulically isolate the sandstone beds, which results in a series of semi-confined and confined sandstone subaquifers with little or different degrees of hydraulic connection (Robinove, 1958a,b; Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Anderson and Kelly, Inc., 1976; Richter, 1981). Nevertheless, lenticular sandstone beds (subaquifers) in the Wind River Formation may have sufficient hydraulic connection to consider the sequence a single aquifer at a regional scale (Anderson and Kelly, Inc., 1976; James Gores and Associates, 1998b). Most wells in the Wind River aquifer are completed in sandstone subaquifers/aquifers of the upper, fine-grained sequence and are relatively low yielding, but the most productive are completed in the middle, coarse-grained sequence developed in the western basin, including the Riverton area, where wells yield as much as several hundred gallons per minute **(Plate IX)** (McGreevy et al., 1969; Anderson and Kelly, Inc., 1976; Mancini, 1977; Richter, 1981; James Gores and Associates, 1998b; Nelson Engineering, 2000a,b; Keller Associates, 2008b). Richter (1981) also noted that permeability in the Wind River aquifer may be fracture enhanced in highly fractured anticlines in the WRB.

Although not highly permeable throughout the WRB (except the permeable middle coarse-grained sequence), the Wind River aquifer is an important source of water for domestic or stock purposes (although quality varies widely). Hydrogeologic data describing the Wind River aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate IX**.

Recharge to the Wind River aquifer is from direct infiltration of precipitation; ephemeral and perennial streamflow losses; infiltration of diverted surface water from unlined irrigation canals, ditches, and laterals; and water applied to fields (Morris et al., 1959; McGreevy et al., 1969). Infiltrating irrigation waters and streamflow losses likely provide most recharge to the aquifer (Morris et al., 1959; Anderson and Kelly, Inc., 1976). Recharge also is likely in areas where the aquifer is overlain by, and in hydraulic connection with, saturated Quaternary-age unconsolidated deposits (alluvium and terrace deposits) (McGreevy et al., 1969).

Discharge from the Wind River aquifer is both natural and anthropogenic. Groundwater naturally discharges from the aquifer through seeps, springs, and gaining streams (Lowry et al., 1976; Richter, 1981). Richter noted numerous springs discharging from the Wind River Formation in the eastern and central Wind River Basin. He noted that spring discharges typically were from sandstone beds perched above less permeable fine-grained rocks. He also noted that spring discharges are highly variable and dependent on seasonal recharge. The primary anthropogenic sources of discharge from the Wind River aquifer are domestic, stock, irrigation, industrial, and public-supply wells.

Excluding the southeastern WRB, regional groundwater flow in the Wind River aquifer is toward the Wind River and Boysen Reservoir (Richter, 1981; James Gores and Associates, 1998b). Regional groundwater flow in the Wind River aquifer in the southeastern WRB is "toward the east with flow converging on Alcova and Pathfinder Reservoirs" (Richter, 1981, p. 83). The direction of groundwater flow has been altered in the Riverton area and is now towards the city because of reduced aquifer pressure as a result of decades of groundwater production in the city's wellfield (James Gores and Associates, 1998b). Keller Associates (2008b, Appendix G) noted that "groundwater levels in the Wind River aquifer have been lowered as a result of municipal groundwater production since 1924"; that "groundwater levels in the Riverton area remain below those of the 1940s"; and that "Riverton's long reliance upon the aquifer has resulted in an area-wide lowering of the water levels in wells by approximately 30 feet."

A MODFLOW groundwater-flow model of the Wind River aquifer was constructed to evaluate the effects of past, current, and future groundwater withdrawals in the Riverton area (James Gores and Associates, 1998b). The model of the Wind River aquifer consisted of a single, 300-foot-thick layer with an area 42,500 by 37,000 ft. The investigators initially conducted

a steady-state simulation and subsequently conducted transient simulations to evaluate numerous groundwater management (pumping) scenarios.

Similar to the Quaternary unconsolidated-deposit aquifers, the areal extent of the Wind River aquifer coincides with much of the rural population and irrigated cropland in the WRB, making these aquifers susceptible to contamination from human activities at the land surface. Evidence of groundwater contamination by human activities has been indicated by detection of elevated nitrate concentrations and of pesticides (Plafcan et al., 1995; Daddow, 1996; Eddy-Miller and Norris, 2000b; Eddy-Miller and Remley, 2005; Bartos et al., 2009). Some of these contaminants may be transported to the Wind River aquifer where it is overlain by Quaternary-age unconsolidated deposits.

Chemical characteristics

The chemical composition of groundwater in the Wind River aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 261 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1, diagram C**). Richter (1981) noted that the predominant anion changes from bicarbonate to sulfate as TDS concentration increases – this relation is clearly evident in the trilinear diagram constructed for this study (**Appendix G1, diagram C**). TDS concentrations were variable and indicated that most waters were fresh (67 percent of samples) and the remaining waters ranged from slightly to moderately saline (**Appendix E1**; **Appendix G1, diagram C**; supplementary data tables). TDS concentrations ranged from 224 to 5,110 mg/L, with a median of 707 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of 47 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram A**). TDS concentrations were variable and indicated that most produced waters were slightly saline (53 percent) and the remaining produced waters were moderately saline to briny (**Appendix F1; Appendix H1, diagram A**; supplementary data tables). TDS concentrations ranged from 1,060 to 38,800 mg/L, with a median of 2,730 mg/L.

Concentrations of some properties and constituents in water from the Wind River aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit their suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (80 percent of samples analyzed for the constituent), uranium (29 percent), ammonia (5 percent), selenium (4 percent), boron (1 percent), nitrate (1 percent), nitrate plus nitrite (1 percent), and fluoride (less than 1 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (64 percent), sulfate (56 percent), pH (32 percent above upper limit), manganese (20 percent), filtered iron (17 percent), fluoride (9 percent), and chloride (2 percent).

Chemical analyses of many properties and constituents were not available for the produced-water samples from the Wind River aquifer; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), chloride (81 percent), sulfate (37 percent), and pH (9 percent below lower limit and 11 percent above upper limit). TDS concentrations in 9 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Wind River aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were SAR (67 percent), sulfate (62 percent), TDS (12 percent), pH (10 percent above upper limit), selenium (8 percent), chloride (6 percent), manganese (5 percent), boron (3 percent), mercury (3 percent), and filtered iron (2 percent). Properties and constituents measured at concentrations greater than livestock-use standards were pH (32 percent above upper limit), selenium (4 percent), sulfate (1 percent), and TDS (less than 1 percent).

Produced-water samples from the Wind River aquifer generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (91 percent), TDS (68 percent), filtered iron (68 percent), and sulfate (42 percent). Produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (26 percent), chloride (17 percent), pH (9 percent below lower limit and 11 percent above upper limit), and sulfate (5 percent).

Several investigators have noted problems with hydrogen sulfide odors in water samples collected from wells completed in the Wind River aquifer (Morris et al., 1959; Stetson Engineering, Inc., 2006a,b). Morris et al. (1959) also noted problems with sulfur precipitation in some groundwater samples.

7.1.6 Indian Meadows confining unit

The lower Eocene-age Indian Meadows Formation comprises the Indian Meadows confining unit in the WRB **(Plate II)**. The Indian Meadows Formation consists of variegated claystone, sandstone, and limestone (Keefer, 1965; Richter, 1981, table IV-1). Reported thickness of the Indian Meadows confining unit ranges from 0 to 750 ft (Richter, 1981, table IV-1). The confining unit separates the overlying Wind River aquifer from the underlying Fort Union-Lance aquifer **(Plate II)**. No data were located describing the physical and chemical characteristics of the hydrogeologic unit.

7.1.7 Fort Union–Lance aquifer

The physical and chemical characteristics of the Fort Union-Lance aquifer in the WRB are described in this section of the report.

Physical characteristics

The Fort Union–Lance aquifer is contained in the Paleocene-age Fort Union Formation and the Upper Cretaceous-age Lance Formation **(Plate II)**. The Fort Union Formation comprises the Fort Union aquifer and the Lance Formation comprises the Lance aquifer in the WRB **(Plate II)**. Although the Fort Union and Lance aquifers can be considered individual aquifers, Richter (1981) combined them into a single aquifer (Fort Union-Lance aquifer) because no regional confining unit separates the formations **(Plate II)**. That approach is maintained herein, although characteristics of both aquifers are described separately.

The Fort Union Formation is overlain by the Indian Meadows Formation and underlain by the Lance Formation **(Plate II)**. The Fort Union Formation is composed of interbedded sandstone, siltstone, mudstones, carbonaceous shales, and coal; the formation can be subdivided into a lower fluvial and paludal interval and an upper fluvial, lacustrine, and marginal lacustrine interval (Keefer, 1961a,b, 1965b, 1969). The lower fluvial and paludal unit, composed of interbedded conglomerate, fine- to coarse-grained sandstone, gray shale, carbonaceous shale, and coal, is defined as the lower unnamed member **(Plate II)**. The upper fluvial and marginal lacustrine interval is divided into two members – the Waltman Shale Member, composed of organic-rich lacustrine shale with interbedded sandstone and siltstone, and the Shotgun Member, composed of fine- to coarse-grained sandstone, conglomerate, siltstone, shale, carbonaceous shale, and coal. None of the three members is present or recognized throughout the WRB (Keefer, 1965b). Conglomerates are a substantial part of the formation in the southwestern WRB (Flores et al., 1993). Reported thickness of the lower unnamed member ranges from less than 500 ft in the southwestern WRB to more than 3,500 ft along the basin trough south of the Bighorn Mountains (Johnson et al., 2007, Figure 16). The thickness of the Waltman Shale Member exceeds 3,800 ft in structurally deep areas near the WRB axis (Keefer, 1997). The Shotgun Member is about 2,830 ft thick at Shotgun Butte and more than 2,200 ft thick near the north margin of the WRB (Keefer, 1961a,b; 1965b).

Sandstones and conglomerates in the Fort Union Formation compose the permeable parts of the Fort Union aquifer (Whitcomb and Lowry, 1968; Richter, 1981; Flores et al., 1993). The Fort Union aquifer is mostly under confined conditions, but unconfined (water-table) conditions are likely in outcrop areas of the Fort Union Formation. Permeability is primarily intergranular, but may be fracture-enhanced in structurally deformed areas (Richter, 1981). Few wells are installed in the Fort Union aquifer, and most are for stock use. Flores et al. (1993, p. 143-144) reported that conglomerates in the southwestern WRB north of Hudson indicated "good aquifer characteristics," and well yields of as much as 12 gal/min led them to conclude that conglomerates in the area could be "a potential water resource." Wester-Wetstein and Associates (2009) drilled an exploratory well into a thick, coarse-grained sandstone sequence in the Fort Union Formation to evaluate the formation as a potential water source for the town of Hudson. Poor well yield and water quality led the investigators to conclude that the aquifer was not "a viable source of water for the Town" (Wester-Wetstein and Associates, 2009, p. 15). Relatively low yield, variable water quality, variable hydrogeologic characteristics, and limited areal extent preclude much aquifer development. Hydrogeologic data describing the Fort Union aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

The Upper Cretaceous-age Lance Formation composes the Lance aquifer in the WRB **(Plate II)**. The Lance Formation consists of sandstone interbedded with shale, claystone, siltstone, and thin coal (Keefer, 1965; Richter, 1981, table IV-1, and references therein). Reported thickness of the Lance Formation ranges from less than 500 ft in the southwestern WRB to more than 6,000 ft along the basin trough south of the Bighorn Mountains (Johnson et al., 2007, Figure 15). The Lance Formation is overlain by the Fort Union Formation and underlain by the Upper Cretaceous-age Meeteetse Formation or Lewis Shale **(Plate II)**. Confined conditions in the Lance aquifer predominate, but unconfined conditions are likely in outcrop areas of the Lance Formation. With the exception of oil and gas wells, few wells have been installed in the aquifer. Richter (1981, table IV-1, p. 48) speculated the aquifer had "large development potential" in the WRB, but poor water quality determined during this study (determined primarily from produced-water samples) would preclude most uses without treatment. Hydrogeologic data describing the Lance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Chemical characteristics

Chemical characteristics of both the Fort Union and Lance aquifers composing the Fort Union-Lance aquifer in the WRB are described in this section of the report.

7.1.7.1 Fort Union aquifer

The chemical composition of groundwater in the Fort Union aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from three wells. Individual constituent concentrations are listed in Appendix E1. TDS concentrations were variable and indicated that two of the three samples had slightly saline water (67 percent of samples) and the remaining sample had moderately saline water (supplementary data tables). TDS concentrations ranged from 1,010 to 5,110 mg/L, with a median of 2,200 mg/L.

The chemical composition of groundwater in the Fort Union aquifer also was characterized and the quality evaluated on the basis of 386 produced-water samples from wells completed in the Fort Union aquifer. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram B**). TDS concentrations from produced-water samples indicated that most waters were moderately saline (68 percent of samples) and the remaining waters ranged from fresh to briny (Appendix F1; Appendix H1, diagram B; supplementary data tables). TDS concentrations ranged from 872 to 69,100 mg/L, with a median of 7,560 mg/L.

Concentrations of some properties and constituents in environmental water samples from the Fort Union aquifer in the WRB 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 (USEPA MCLs and HALs): ammonia (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (100 percent), filtered iron (100 percent), fluoride (50 percent), pH (33 percent above upper limit), and sulfate (33 percent).

Chemical analyses of many properties and constituents were not available for the produced-water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (SMCLs) for domestic use: TDS (100 percent), manganese (100 percent), radium-226 plus radium-228 (100 percent), chloride (93 percent), filtered iron (89 percent), sulfate (17 percent), and pH (4 percent below lower limit and 16 percent above upper limit). TDS concentrations in 20 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Fort Union aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were SAR (100 percent), chloride (100 percent), TDS (67 percent), and sulfate (33 percent). Properties and constituents that had concentrations greater than livestock-use standards were pH (33 percent above upper limit), TDS (33 percent), and sulfate (33 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (97 percent), TDS (96 percent), filtered iron (57 percent), sulfate (21 percent), and pH (2 percent above upper limit). The produced-water samples had concentrations of two properties and two constituents that exceeded livestock-use standards: TDS (75 percent), chloride (62 percent), pH (4 percent below lower limit and 16 percent above upper limit), and sulfate (1 percent).

7.1.7.2 Lance aquifer

The chemical composition of groundwater in the Lance aquifer in the WRB was characterized and the quality evaluated on the basis of 80 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram C**). TDS concentrations were variable and indicated that most waters were moderately saline (74 percent of samples) and the remaining waters ranged from slightly saline to briny (**Appendix F1; Appendix H1, diagram C**; supplementary data tables). TDS concentrations ranged from 1,680 to 113,000 mg/L, with a median of 6,720 mg/L.

Concentrations of some properties and constituents in water from the Lance aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of one constituent that always exceeded health-based standards (USEPA MCLs and HALs): barium (100 percent of samples analyzed for the constituent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs)

for domestic use: TDS (100 percent of samples analyzed for the property), chloride (98 percent), filtered iron (96 percent), sulfate (25 percent), and pH (5 percent below lower limit and 14 percent above upper limit). TDS concentrations in 21 percent of produced-water samples from the Lance aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (100 percent), TDS (99 percent), filtered iron (65 percent), sulfate (31 percent), and pH (1 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (78 percent), chloride (72 percent), and pH (5 percent below lower limit and 14 percent above upper limit).

7.1.8 Meeteetse–Lewis confining unit

The physical and chemical characteristics of the Meeteetse–Lewis confining unit in the WRB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Meeteetse Formation and Lewis Shale compose the Meeteetse–Lewis confining unit in the WRB **(Plate II)**. The Meeteetse Formation consists of massive to thin bedded sandstone interbedded with shale, claystone, siltstone, mudstone, and occasional thin coal, whereas the Lewis Shale consists primarily of shale (Richter, 1981, and references therein; Johnson et al., 2007). Where present, the Lewis Shale is interbedded with the Meeteetse Formation **(Plate II)**. Reported thickness of the Meeteetse–Lewis confining unit ranges from 500 ft in the southwestern part of the WRB to more than 1,750 ft along the basin trough south of the Bighorn Mountains (Johnson et al., 2007, Figure 14). Thickness estimates of the Lewis Shale in the WRB were not located. The Meeteetse Formation and Lewis Shale are overlain by the Lance Formation and underlain by the Mesaverde Formation **(Plate II)**. Hydrogeologic data describing the Meeteetse–Lewis confining unit in the WRB, including well-yield and spring-discharge measurements and other hydraulic properties, were not available.

Chemical characteristics

Groundwater-quality samples were available from only one of the lithostratigraphic units (Lewis Shale) composing the Meeteetse–Lewis confining unit in the WRB. The chemical composition of groundwater in the Meeteetse–Lewis confining unit in the WRB was characterized and the quality evaluated on the basis of two produced-water samples from wells completed in the Lewis Shale. Individual constituent concentrations are listed in **Appendix F1**. TDS concentrations (4,020 and 5,250 mg/L) indicated that both waters were moderately saline.

Concentrations of some properties and constituents in water from the Meeteetse–Lewis confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Analyses for many properties and constituents were not available from the produced-water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one property and two constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), chloride (50 percent of samples analyzed for the constituent), and sulfate (50 percent).

Concentrations of some properties and constituents in water from the Meeteetse–Lewis confining unit exceeded State of Wyoming standards for agricultural and livestock use in the WRB. The produced-water samples had concentrations of one property and two constituents that exceeded agricultural-use standards: TDS (100 percent), chloride (50 percent), and sulfate (50 percent). The produced-water samples generally had concentrations of one property that exceeded livestock-use standards: TDS (50 percent).

7.1.9 Mesaverde aquifer

The physical and chemical characteristics of the Mesaverde aquifer in the WRB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Mesaverde Formation comprises the Mesaverde aquifer in the WRB **(Plate II)**. The Mesaverde Formation consists of a variable sequence of massive lenticular fine- to coarse-grained sandstone, carbonaceous shale, and lesser amounts of coal (Johnson et al., 2007, and references therein). Reported thickness of the Mesaverde Formation (including all members) ranges from 500 ft in the eastern WRB to 2,200 ft in the western WRB (Johnson et al., 2007, fig. 9). As many as four members of the Mesaverde Formation are recognized in the eastern WRB – the uppermost Teapot Sandstone Member, the middle unnamed member, the Parkman Sandstone Member, and the lowermost Fales Sandstone Member **(Plate II)** (Johnson et al., 2007, and references therein). The Wallace Creek Tongue of the Cody Shale separates the Parkman and Fales Sandstone Members **(Plate II)**. In the southern, central, and western WRB, the Mesaverde Formation is subdivided into the Teapot Sandstone Member and an underlying informally named "lower part" (not shown on Plate II; see Johnson et al., 2007, Figure 2). As their names imply, the Teapot Sandstone,

Parkman Sandstone, and Fales Sandstone Members are composed primarily of sandstone, and these members are defined as aquifers or subaquifers (Richter, 1981; **Plate II**). The unnamed middle member is composed of siltstone, shale, carbonaceous shale, and thin-bedded, discontinuous sandstone; this member and the intertonguing Wallace Creek Tongue of the Cody Shale are defined as confining units (Richter, 1981; **Plate II**). Both these confining units, along with the regionally extensive Meeteetse-Lewis and Cody confining units, create the series of confined sandstone subaquifers (Teapot Sandstone, Parkman Sandstone, and Fales Sandstone aquifers) composing the Mesaverde aquifer **(Plate II)**. In some parts of the WRB, the sandstone subaquifers may be hydraulically connected by faults and fractures in underlying and overlying confining units (Richter, 1981).

Fluvial channel sandstones in the Mesaverde Formation typically range from about 10 to 35 ft thick, but commonly are "stacked and amalgamated" into units exceeding 100 ft in thickness (Johnson et al., 1996, p. 14; Johnson et al., 2007). The Teapot Sandstone aquifer likely has the best potential for development; Johnson et al. (2007, p. 14) noted that "the tendency toward amalgamation is greatest in the Teapot Sandstone Member at the top of the Mesaverde Formation, particularly in the western basin where the Teapot Sandstone may be more than 500 ft thick and consists predominantly of stacked sandstones to more than 120 ft thick" (Johnson et al., 1996; Johnson et al., 2007).

Confined conditions predominate, but unconfined (water-table) conditions are likely in outcrop areas of the Mesaverde Formation. Hydrogeologic data describing the Mesaverde aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Permeability may be enhanced in areas where the Mesaverde aquifer is faulted and fractured. Several fault-controlled springs southeast of Riverton near the head of Kirby Draw discharge 20 to 100 gal/min (Richter, 1981, p. 79).

Excluding oil and gas production, few wells are installed in the Mesaverde aquifer. Sandstone beds within the aquifer have potential for development for stock, domestic, or limited public-supply use, although poor water quality determined during this study would preclude many uses without treatment.

Recharge to the Mesaverde aquifer is primarily by infiltration of precipitation and streamflow on outcrops (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). Richter (1981, p. 80) noted that "recharge by precipitation largely occurs in the Casper Arch, Gas Hills, and Owl Creek Mountain areas" and that "large recharge potential exists where the Wind, Little Wind, and Popo Agie Rivers cross permeable Mesaverde sandstone exposures." Where the Mesaverde Formation is buried, interformational flow also may contribute to aquifer recharge (McGreevy et al., 1969).

Discharge from the Mesaverde aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). Some of the discharge from springs is where streams have eroded the aquifer (McGreevy et al., 1969). The primary anthropogenic source of discharge is oil and gas wells.

Chemical characteristics

The chemical composition of groundwater in the Mesaverde aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations for the two samples are listed in **Appendix E1**. TDS concentrations (1,100 and 1,470 mg/L) indicated that both waters were slightly saline.

The chemical composition of groundwater in the Mesaverde aquifer also was characterized and the quality evaluated on the basis of 48 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram D**). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, and most of the water was moderately saline (69 percent) (**Appendix F1; Appendix H1, diagram D**; supplementary data tables). TDS concentrations ranged from 1,710 to 15,300 mg/L, with a median of 4,710 mg/L.

Concentrations of some properties and constituents in the Mesaverde aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Waters from both environmental samples were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): fluoride (50 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), pH (50 percent above upper limit), fluoride (50 percent), and sulfate (50 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use

standards were limited. The few produced-water samples with available analyses had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): lead (100 percent) and barium (100 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), aluminum (100 percent exceeded lower and upper limits), filtered iron (100 percent), manganese (100 percent), chloride (71 percent), sulfate (48 percent), and pH (10 percent below lower limit and 12 percent above upper limit). TDS concentrations in 10 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Mesaverde aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were pH (50 percent above upper limit), SAR (50 percent), and sulfate (50 percent). One property had values greater than livestock-use standards: pH (50 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: manganese (100 percent), TDS (94 percent), chloride (85 percent), filtered iron (67 percent), and sulfate (48 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (44 percent), chloride (29 percent), pH (10 percent below lower limit and 12 percent above upper limit), and sulfate (5 percent).

7.1.10 Cody confining unit

The physical and chemical characteristics of the Cody confining unit in the WRB are described in this section of the report.

Physical characteristics

The regionally extensive Cody confining unit is composed of the Upper Cretaceous-age Cody Shale. This thick unit regionally confines and separates the underlying lower and middle Mesozoic aquifers and confining units from the overlying Mesaverde aquifer **(Plate II)**. Reported thickness of the Cody Shale ranges from about 3,250 ft in the western basin to as much as 5,500 ft in the eastern basin (Johnson et al., 2007). The Cody Shale is composed primarily of marine shale with some sandstone and siltstone (Richter, 1981; Johnson et al., 2007, and references therein). Sandstones in the "upper sandy member" of the Cody Shale are important oil and gas reservoirs in the WRB (Johnson et al., 2007). Sandstones and fractured zones in the formation may yield small quantities of water to wells at some locations, although poor water quality can limit many uses. Hydrogeologic information available describing the Cody confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Cody confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 12 wells. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram **(Appendix G1, diagram D**). TDS concentrations were variable and indicated that most waters were slightly saline (55 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E1**; **Appendix G1, diagram D**; supplementary data tables). TDS concentrations ranged from 451 to 6,850 mg/L, with a median of 1,750 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of 40 produced-water samples from wells completed in the Cody confining unit. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram E**). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, but most water was moderately saline (69 percent) (**Appendix F1; Appendix H1, diagram E**; supplementary data tables). TDS concentrations ranged from 299 to 24,000 mg/L, with a median of 5,620 mg/L.

Concentrations of some properties and constituents in water from the Cody confining unit in the WRB 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 a few constituents exceeded health-based standards (USEPA MCLs and HALs): nitrate (50 percent of samples analyzed for the constituent), ammonia (33 percent), selenium (33 percent), and nitrate plus nitrite (20 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (91 percent), sulfate (91 percent), manganese (67 percent), filtered iron (50 percent), pH (20 percent above upper limit), and fluoride (9 percent).

Chemical analyses of many properties and constituents were not available for the produced-water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA MCLs and HALs) for domestic use: TDS (98 percent), iron

(100 percent), chloride (88 percent), pH (14 percent below lower limit and 22 percent above upper limit), and sulfate (16 percent). TDS concentrations in 18 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Cody confining unit exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (91 percent), SAR (55 percent), TDS (45 percent), selenium (33 percent), and chloride (9 percent). Properties and constituents that had concentrations greater than livestock-use standards were selenium (33 percent), pH (20 percent above upper limit), TDS (18 percent), and sulfate (18 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (90 percent), TDS (85 percent), filtered iron (60 percent), sulfate (20 percent), and pH (3 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (55 percent), chloride (52 percent), and pH (14 percent below lower limit and 22 percent above upper limit).

7.1.11 Lower and middle Mesozoic aquifers and confining units

In the WRB, the lower and middle Mesozoic aquifers and confining units is a stratigraphic and hydrogeologic sequence generally composed of impermeable fine-grained rocks (for example, shale) that isolate discrete water-bearing sandstone units. Rocks composing the hydrogeologic sequence range in age from Lower Triassic to Upper Cretaceous **(Plate II)**. The complex intertonguing and interfingering relation between the different facies within the sequence creates numerous small permeable zones that can function as individual aquifers (or subaquifers). In addition, many of the lithostratigraphic units within this sequence consist of more than one sequence/facies, some of which function as confining units (shales and siltstones) and some as aquifers (sandstones and carbonates) **(Plate II)**.

Numerous oil and gas wells are completed in many of the formations composing the lower and middle Mesozoic aquifers and confining units, but relatively few water wells are completed, with most in outcrop areas around the basin margin where drilling depths are relatively shallow and waters are relatively fresh. Most of these wells are completed for domestic or stock purposes. Most geologic and hydrogeologic data for the lower and middle Mesozoic aquifers and confining units are from petroleum exploration. Groundwater in many of the hydrogeologic units, especially away from outcrop areas, is highly mineralized and unsuitable for most uses.

7.1.11.1 Frontier aquifer

The physical and chemical characteristics of the Frontier aquifer in the WRB are described in this section of the report.

Physical characteristics

The upper part of the Upper Cretaceous-age Frontier Formation comprises the Frontier aquifer in the WRB. The Frontier Formation is present throughout the WRB except in the Granite Mountains area, and crops out along the Wind River Range, Owl Creek Mountains, Gas Hills, and Casper Arch **(Plate I)**. The Frontier Formation is composed of an alternating sequence of very-fine- to medium-grained sandstone and shale in three stratigraphic members – the lowermost Belle Fourche Member, the middle Emigrant Gap Member, and the uppermost Wall Creek Sandstone Member (Johnson et al., 2007, and references therein). Reported thickness of the Frontier Formation (all three members) in the WRB ranges from about 700 to 1,200 ft, with the thickest sections in the south-central Wind River Basin (Johnson et al., 2007, and references therein). The middle Emigrant Gap Member and the uppermost Wall Creek Sandstone Member compose the Frontier aquifer, whereas the lowermost Belle Fourche Member composes a basal regional confining unit **(Plate II)**. The Frontier aquifer is confined from above by the thick regional Cody confining unit and below by the Mowry–Thermopolis confining unit **(Plate II)**. The Frontier aquifer is the uppermost unit of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence **(Plate II)**.

Alternating layers of sandstone and shale create a series of confined sandstone subaquifers within the Frontier aquifer (Richter, 1981, p. 76). Total sandstone thickness ranges from about 85 to 280 ft (Johnson et al., 1996). Sandstone beds within the aquifer are utilized for stock and domestic use, most commonly along the Wind River Range (Whitcomb and Lowry, 1968; Richter, 1981). Water in the aquifer generally is under confined and semiconfined conditions (Whitcomb and Lowry, 1968; Richter, 1981). Hydrogeologic information describing the Frontier aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Frontier aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 17 wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix**

G1, diagram E). TDS concentrations were variable and indicated that waters ranged from fresh to moderately saline (**Appendix E1; Appendix G1, diagram E**; supplementary data tables). TDS concentrations ranged from 280 to 9,060 mg/L, with a median of 1,170 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of 38 produced-water samples from wells completed in the Frontier aquifer. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram F**). TDS concentrations from produced waters were highly variable and indicated that most waters were moderately saline (50 percent of samples) and the remaining waters ranged from fresh to briny (**Appendix F1; Appendix H1, diagram F**; supplementary data tables). TDS concentrations ranged from 219 to 43,700 mg/L, with a median of 9,590 mg/L.

Concentrations of some properties and constituents in the Frontier aquifer in the WRB 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 (USEPA MCLs and HALs): boron (40 percent of samples analyzed for the constituent) and nitrate (17 percent). Concentrations of several properties and constituents exceeded aesthetic standards for domestic use: TDS (68 percent), sulfate (53 percent), manganese (25 percent), filtered iron (17 percent), chloride (11 percent), pH (6 percent above upper limit), and fluoride (6 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USPEA SMCLs) for domestic use: TDS (97 percent), chloride (95 percent), filtered iron (75 percent), sulfate (24 percent), and pH (3 percent below lower limit and 21 percent above upper limit). TDS concentrations in 45 percent of produced-water samples from the Frontier aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Frontier aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were boron (60 percent), SAR (53 percent), sulfate (53 percent), TDS (32 percent), manganese (25 percent), chloride (21 percent), and filtered iron (17 percent). Properties and constituents that had concentrations greater than livestock-use standards were TDS (21 percent), sulfate (16 percent), pH (6 percent above upper limit), and chloride (5 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (97 percent), chloride (95 percent), iron (50 percent), and sulfate (24 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (84 percent), chloride (82 percent), and pH (3 percent below lower limit and 21 percent above upper limit).

7.1.11.2 Mowry–Thermopolis confining unit

The physical and chemical characteristics of the Mowry–Thermopolis confining unit in the WRB are described in this section of the report.

Physical characteristics

The Mowry–Thermopolis confining unit is composed primarily of the the Upper Cretaceous-age Mowry Shale and the Lower Cretaceous-age Thermopolis Shale, but also contains the Lower Cretaceous-age Muddy Sandstone **(Plate II)**. The Mowry Shale is a confining unit that primarily consists of siliceous shale and bentonite and ranges in thickness from about 395 to 560 ft (Nixon, 1973; Byers and Larson, 1979; Richter, 1981, table IV-1, and references therein). The Muddy Sandstone comprises the Muddy Sandstone aquifer, an aquifer confined above by the Mowry Shale and below by the Thermopolis Shale **(Plate II)**. The Muddy Sandstone (formerly considered a member of the Thermopolis Shale) is composed of massive sandstone interbedded with mudstone, and ranges from 20 to 134 ft in thickness (Dresser, 1974). The Muddy Sandstone is a major oil and gas reservoir in the WRB. Permeability in the Muddy Sandstone aquifer is generally low because of tight cementation and silty matrix; however, permeability can be fracture enhanced in areas of deformation such as the Rattlesnake Hills and Casper Arch (Richter, 1981, p. 75). The Thermopolis Shale is a confining unit that is primarily composed of shale and siltstone and ranges in thickness from about 100 to 175 ft; the shale is dark gray to black and contains thin layers of siltstone, sandy claystone, and bentonite (Burtner and Warner, 1984; Johnson et al., 2007, and references therein). The thick Mowry–Thermopolis confining unit separates the underlying Cloverly aquifer from the overlying Frontier aquifer **(Plate II)**.

With the exception of oil and gas wells, very few wells are installed in the Mowry–Thermopolis confining unit; development is likely limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Most information describing the formations is from oil and gas well data. Hydrogeologic

information available describing the Mowry–Thermopolis confining unit, including well-yield and spring-discharge measurements and other hydraulic properties for all three lithostratigraphic units composing the hydrogeologic unit, are summarized on **Plate IX**.

Chemical characteristics

Chemical characteristics of the Mowry confining unit, the Muddy Sandstone aquifer, and the Thermopolis confining unit, which compose the Mowry–Thermopolis confining unit in the WRB, are presented and described in this section of the report.

7.1.11.2.1 Mowry confining unit

The chemical composition of groundwater in the Mowry confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from one well (nutrient analyses only) and one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (648 mg/L) of the spring sample indicated that the water was fresh.

Concentrations of some properties and constituents in the Mowry confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations in the spring sample exceeded health-based standards (USEPA MCLs and HALs). TDS and sulfate concentrations in the spring sample exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Concentrations of SAR and sulfate were greater than agricultural-use standards. No concentrations of properties or constituents exceeded State of Wyoming livestock standards in the one spring sample.

7.1.11.2.2 Muddy Sandstone aquifer

The chemical composition of groundwater in the Muddy Sandstone aquifer in the WRB was characterized and the quality evaluated on the basis of 12 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1, diagram G**). TDS concentrations from produced waters were variable and indicated that most waters were moderately saline (83 percent of samples) and the remaining waters were slightly saline (**Appendix F1; Appendix H1, diagram G**; supplementary data tables). TDS concentrations ranged from 1,220 to 9,610 mg/L, with a median of 6,060 mg/L.

Concentrations of some properties and constituents in the Muddy Sandstone aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. All available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the chemical analyses from produced-water samples could be compared with health-based standards because USEPA MCLs or HALs were not available for the constituents analyzed. The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the property), filtered iron (100 percent), chloride (67 percent), sulfate (36 percent), and pH (9 percent below lower limit).

Concentrations of some properties and constituents in the Muddy Sandstone aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: filtered iron (100 percent), TDS (92 percent), chloride (91 percent), and sulfate (45 percent). The produced-water samples had concentrations of two properties and one constituent that exceeded livestock-use standards: TDS (58 percent), chloride (42 percent), and pH (9 percent below lower limit).

7.1.11.2.3 Thermopolis confining unit

The chemical composition of groundwater in the Thermopolis confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations for these samples are listed in **Appendix E1**. TDS concentrations (223 and 525 mg/L) indicated that the waters were fresh.

Concentrations of some properties and constituents in water from the Thermopolis confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of two properties and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use in the water sample from the well: pH (below lower limit), TDS, and sulfate.

Concentrations of few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. In the sample from the well, the sulfate concentration was greater than agricultural-use standards and the pH value was outside the livestock-use standard range (below lower limit).

7.1.11.3 Cloverly aquifer

The physical and chemical characteristics of the Cloverly aquifer in the WRB are described in this section of the report.

Physical characteristics

The Lower Cretaceous-age Cloverly Formation comprises the Cloverly aquifer in the WRB **(Plate X)**. The Cloverly Formation consists of three informally divided units – an upper sandstone interbedded with lenticular cherty pebble conglomerate and thin variegated shale known as the "Dakota Sandstone"; a middle shale unit known as the "Fuson Shale"; and a basal fine- to coarse-grained sandstone known as the "Lakota Sandstone" (Richter, 1981). Reported thickness of the Cloverly Formation, including all three lithologic units, ranges from about 200 to 300 ft (Richter, 1981, p. 72). Richter (1981, p. 72-73) considered the middle shale unit to be a leaky confining unit separating the two sandstone units, which he defined as confined subaquifers within the Cloverly aquifer. The Cloverly aquifer is part of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence **(Plate II)**. The aquifer is confined above by the Mowry-Thermopolis confining unit and below by the Morrison confining unit **(Plate II)**. Excluding petroleum production, most wells are installed for domestic or stock use in areas where the Cloverly Formation crops out and water quality is acceptable (Richter, 1981; Plafcan et al., 1995, table 16). Hydrogeologic information describing the Cloverly aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate IX**.

Permeability of the Cloverly aquifer is primarily secondary and dependent upon fracturing (Richter, 1981). Richter reported that permeabilities of the Cloverly aquifer were much greater in deformed (folded and faulted) areas with many fractures than in relatively undeformed areas with few fractures.

Chemical characteristics

The chemical composition of groundwater in the Cloverly aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from eight wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (67 percent of samples) and the remaining waters were slightly saline (supplementary data tables). TDS concentrations ranged from 214 to 1,500 mg/L, with a median of 792 mg/L.

The chemical composition of groundwater in the Cloverly aquifer in the WRB was characterized and the quality evaluated on the basis of 19 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, diagram H). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline; however, the concentrations indicated that most of the water was moderately saline (53 percent) (**Appendix F1; Appendix H1**, diagram H; supplementary data tables). TDS concentrations ranged from 1,110 to 30,000 mg/L, with a median of 5,370 mg/L.

Concentrations of some properties and constituents in the Cloverly aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all environmental water samples were suitable for domestic use. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (100 percent of samples analyzed for the constituent), TDS (56 percent), sulfate (44 percent), fluoride (22 percent), and pH (11 percent above upper limit).

For produced-water samples, few analyses of properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples), chloride (79 percent), sulfate (68 percent), filtered iron (50 percent), and pH (4 percent above upper limit). TDS concentrations in 26 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Cloverly aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (56 percent), boron (50 percent), SAR (44 percent), and pH (11 percent above upper limit). One property had values greater than livestock-use standards: pH (11 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded agricultural-use standards: TDS (84 percent), chloride (84 percent), sulfate (74 percent), and filtered iron (50 percent). The produced-water samples had concentrations of one property and one constituent that exceeded livestock-use standards: TDS (58 percent) and chloride (58 percent).

7.1.11.4 Morrison confining unit

The physical and chemical characteristics of the Morrison

confining unit in the WRB are described in this section of the report.

Physical characteristics

The Upper Jurassic-age Morrison Formation comprises the Morrison confining unit in the WRB. The Morrison Formation is composed of variegated claystone and shale with thin interbedded lenticular, fine- to medium-grained friable sandstone (Richter, 1981, table IV-1, and references therein). The fine-grained rocks (claystone and shale) are unlikely to yield water, but interbedded sandstone beds may yield small quantities of water for domestic or stock use where water quality is adequate (Whitcomb and Lowry, 1968; Richter, 1981). The thickness of the Morrison Formation in the WRB is not known, but estimates of thickness for the undivided Cloverly and Morrison Formations ranges from 300 to 570 ft (Richter, 1981, table IV-1, and references therein). The Morrison confining unit is part of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence **(Plate II)**. The Morrison Formation is overlain by the Cloverly Formation and underlain by the Sundance Formation **(Plate II)**. Confined conditions likely predominate, except in outcrop areas. Sandstone beds within the formation are considered to have limited potential for development because of small outcrop area and small yields adequate only for stock or domestic use (Dana, 1962a; Whitcomb and Lowry, 1968; Richter, 1981). Very few wells are installed in the Morrison confining unit. Little hydrogeologic information is available describing the Morrison confining unit, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Morrison confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in Appendix E1. TDS concentrations (867 and 1,740 mg/L) indicated that waters were fresh and slightly saline.

The chemical composition of groundwater in the Morrison confining unit in the WRB also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F1. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, but most of the water was moderately saline (44 percent) (Appendix F1; supplementary data tables). TDS concentrations ranged from 1,090 to 12,000 mg/L, with a median of 4,960 mg/L.

Concentrations of some properties and constituents in water from the Morrison confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), pH (50 percent above upper limit), and fluoride (50 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (78 percent), and sulfate (78 percent). TDS concentrations in 22 percent of produced-water samples from the Morrison confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Morrison confining unit exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were SAR (100 percent), boron (100 percent), sulfate (100 percent), and pH (50 percent above upper limit). One property had values greater than livestock-use standards: pH (50 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (89 percent), TDS (78 percent), and sulfate (78 percent). The produced-water samples had concentrations of one property and one constituent that exceeded livestock-use standards: chloride (56 percent) and TDS (44 percent).

7.1.11.5 Sundance–Nugget aquifer

The physical and chemical characteristics of the Sundance–Nugget aquifer in the WRB are described in this section of the report.

Physical characteristics

The Middle and Upper Jurassic-age Sundance Formation, which contains the Sundance aquifer, and the Jurassic(?)- and Triassic(?)-age Nugget Sandstone, which contains the Nugget

aquifer, plus, in some areas, the intervening Middle Jurassic-age Gypsum Spring Formation, compose the Sundance–Nugget aquifer in the WRB. The Sundance Formation is composed of an upper unit that includes fine- to coarse-grained glauconitic sandstone with some thin shale and fossiliferous limestone interbeds, and a basal unit that includes siltstone and sandstone that grades downward into oolitic limestone, dolomite, and cherty pebble conglomerate (Richter, 1981, table IV-1, and references therein). The Nugget Sandstone is composed of an upper unit that includes fine- to medium-grained, calcite and silica cemented, crossbedded sandstone, and a basal unit that includes calcareous siltstone and mudstone, thin limestone, and thin to massive very fine-grained sandstone (Richter, 1981, table IV-1, and references therein). Permeability is intergranular in both the Sundance and Nugget aquifers (Richter, 1981, table IV-1). Secondary permeability may be developed in some areas with fractures (Whitcomb and Lowry, 1968). Reported thickness of the hydrogeologic unit in the WRB ranges from 200 to 900 ft (Richter, 1981, p. 71). The Sundance–Nugget aquifer is part of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence **(Plate II)**. The Sundance Formation, Gypsum Spring Formation, and Nugget Sandstone are overlain by the Morrison Formation and underlain by the Chugwater Formation. Where it is present as a definable unit, the Gypsum Spring confining unit, described in the next paragraph, separates the Sundance aquifer from the Nugget aquifer **(Plate II)**. Confined conditions predominate except in outcrop areas (Richter, 1981, table IV-1). The Sundance–Nugget aquifer is present throughout the WRB except in the Granite Mountains area. Throughout most of the WRB, the aquifer is deeply buried except in outcrop areas along the Wind River Range and Owl Creek Mountains **(Plate I)**. Sandstone beds within the aquifer are considered to have limited potential for development because of small outcrop extent and small yields adequate only for stock or domestic use (Whitcomb and Lowry, 1968; Richter, 1981). Poor water quality determined during this study would preclude most uses without treatment. Little hydrogeologic information is available describing the Sundance–Nugget aquifer, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

The Gypsum Spring Formation comprises the Gypsum Spring confining unit in the WRB. The Gypsum Spring confining unit, present only in the western two-thirds of the WRB, is composed of an upper unit with an alternating sequence of siltstone, shale, limestone, dolomite, and gypsum, and a basal unit composed of sandy siltstone and silty shale beds (Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein). Reported thickness of the Gypsum Spring Formation in the WRB ranges from 0 to 230 ft (Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein). The Gypsum Spring confining unit is part of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence **(Plate II)**. Where present in the WRB, the Gypsum Spring Formation is overlain by the Sundance Formation and underlain by the Nugget Sandstone **(Plate II)**. Confined conditions likely predominate in the hydrogeologic unit, except in outcrop areas.

No wells were located that are completed in the Gypsum Spring confining unit. Potential for development for any use is very limited because of small outcrop extent, probable poor water quality, and availability of better groundwater sources (Whitcomb and Lowry, 1968). Very little hydrogeologic information is available describing the Gypsum Spring confining unit, but spring discharges are summarized on **Plate IX**.

Chemical characteristics

Groundwater-quality data are presented and described for the Sundance aquifer, Gypsum Spring confining unit, and Nugget aquifer, which compose the Sundance–Nugget aquifer in the WRB.

7.1.11.5.1 Sundance aquifer

The chemical composition of groundwater in the Sundance aquifer in the WRB was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in Appendix E1. The TDS concentration (331 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for, the quality of water from Sundance aquifer in the WRB was likely suitable for most uses. No concentrations of properties or constituents in the Sundance aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental water sample.

The chemical composition of groundwater in the Sundance aquifer in the WRB also was characterized and the quality evaluated on the basis of eight produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F1. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, but concentrations indicated that most of the water was very saline (62 percent) (Appendix F1; supplementary data tables). TDS concentrations ranged from 1,760 to 29,500 mg/L, with a median of 14,500 mg/L.

For the produced-water samples, few analyses of properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for

domestic use: TDS (100 percent of samples analyzed for the property), chloride (88 percent), sulfate (88 percent), and pH (25 percent below lower limit). TDS concentrations in 62 percent of produced-water samples from the Sundance aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded agricultural-use standards: TDS (88 percent), chloride (88 percent), and sulfate (88 percent). The produced-water samples had concentrations of two properties and two constituents that frequently exceeded livestock-use standards: TDS (75 percent), chloride (75 percent), sulfate (62 percent), and pH (25 percent below lower limit).

7.1.11.5.2 Gypsum Spring confining unit

The chemical composition of groundwater in the Gypsum Spring confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (67 percent of samples); the remaining water was slightly saline (**Appendix E1**). TDS concentrations ranged from 287 to 1,360 mg/L, with a median of 383 mg/L.

Concentrations of some properties and constituents in the Gypsum Spring confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (33 percent of samples analyzed for the property) and sulfate (33 percent).

One constituent (sulfate) was measured in one of the three environmental water samples (33 percent) at a concentration greater than agricultural-use standards. No concentrations of properties or constituents exceeded State of Wyoming livestock standards.

7.1.11.5.3 Nugget aquifer

The chemical composition of groundwater in the Nugget aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations indicated that the waters were fresh to slightly saline **(Appendix E1**; supplementary data tables). TDS concentrations were 272 and 1,470 mg/L.

The chemical composition of groundwater in the Nugget aquifer also was characterized and the quality evaluated on the basis of 34 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, diagram I). TDS concentrations from produced-water samples were variable and ranged from slightly saline to briny; however, the concentrations indicated that most of the water was moderately saline (41 percent) (**Appendix F1; Appendix H1**, diagram I; supplementary data tables). TDS concentrations ranged from 1,200 to 217,000 mg/L, with a median of 6,520 mg/L.

Concentrations of some properties and constituents in the Nugget aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for all uses. On the basis of comparison of concentrations in the two environmental water samples with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Sulfate commonly exceeded aesthetic standards (USEPA SMCLs) for domestic use (50 percent of samples analyzed for the constituent).

Most available water-quality analyses for the Nugget aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. No concentrations from produced-water samples were available for comparison with health-based standards (USEPA MCLs and HALs). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), sulfate (97 percent), chloride (76 percent), and pH (3 percent below lower limit and 3 percent above upper limit). TDS concentrations in 44 percent of produced-water samples from the Nugget aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. One property and one constituent in environmental water samples had concentrations greater than agricultural-use standards: SAR (50 percent) and sulfate (50 percent). No concentrations in the two environmental water samples exceeded livestock-use standards.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: iron (100 percent), chloride (97 percent), sulfate (97 percent), and TDS (91 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: chloride

(44 percent), TDS (65 percent), sulfate (50 percent), and pH (3 percent below lower limit and 3 percent above upper limit).

7.1.11.6 Chugwater–Dinwoody aquifer and confining unit

The physical and chemical characteristics of the Chugwater–Dinwoody aquifer and confining unit in the WRB are described in this section of the report.

Physical characteristics

The Chugwater–Dinwoody aquifer and confining unit is composed of the Lower and Upper Triassic-age Chugwater Group or Formation and the Lower Triassic-age Dinwoody Formation. The unit is part of the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence. The Chugwater and Dinwoody Formations are overlain by the Sundance and Nugget Formations and underlain by the Goose Egg and Phosphoria Formations **(Plate II)**. The Chugwater Group contains the Chugwater aquifer and is composed of four lithostratigraphic units – the uppermost unit, the Popo Agie Formation, composed of reddish siltstone, shale, and silty sandstone, ranging in thickness from 0 to 300 ft; the next lower unit, the Crow Mountain Sandstone, composed of red to orange, fine- to coarse-grained sandstone and siltstone, ranging in thickness from 0 to 130 ft; the next lower unit, the Alcova Limestone, composed of hard, finely crystalline limestone, ranging in thickness from 0 to 30 ft; and the lowermost unit, the Red Peak Formation, composed of interbedded reddish siltstone, shale, mudstone, and fine-grained silty sandstone, ranging in thickness from 900 to 950 ft (McGreevy et al., 1969; Richter, 1981, table IV-1, and references therein). The Dinwoody Formation comprises the Dinwoody confining unit and is composed of interbedded sandy dolomitic sandstone, calcareous sandstone, and thin dolomite and limestone (Richter, 1981, table IV-1, and references therein). The Popo Agie Formation, Alcova Limestone, and Dinwoody Formation are confining units; the Crow Mountain and Red Peak Formations are aquifers or subaquifers (**Plate II**; Richter, 1981, table IV-1). Consequently, the Chugwater–Dinwoody aquifer and confining unit may be considered a sequence of rocks that functions as both confining or leaky confining unit and aquifer **(Plate II)**. The Crow Mountain and Red Peak aquifers/subaquifers may yield small quantities of water to wells and springs at some locations in the WRB. Little hydrogeologic information is available describing the Chugwater–Dinwoody aquifer and confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for both formations composing the hydrogeologic unit are summarized on **Plate IX**.

Chemical characteristics

Groundwater-quality data are presented and described for the Chugwater aquifer and Dinwoody confining unit that compose the Chugwater–Dinwoody aquifer and confining unit. Groundwater-quality samples from the Chugwater aquifer generally were available or assigned only for the Chugwater Group, and not for the four stratigraphic members composing the group in the WRB.

7.1.11.6.1 Chugwater aquifer

The chemical composition of groundwater in the Chugwater aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from seven wells and six springs. Summary statistics calculated for available constituents are listed in Appendix E1. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G1, diagram F).TDS concentrations were variable and indicated that most waters were fresh (70 percent of samples) and the remaining waters were slightly saline (Appendix E1; Appendix G1, diagram F; supplementary data tables). TDS concentrations ranged from 211 to 1,640 mg/L, with a median of 669 mg/L.

The chemical composition of groundwater in the Chugwater aquifer also was characterized and the quality evaluated on the basis of 175 produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F1. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H1, diagram J). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny; concentrations indicated that most of the waters were moderately saline (47 percent) (Appendix F1; Appendix H1, diagram J; supplementary data tables). TDS concentrations ranged from 1,010 to 72,100 mg/L, with a median of 5,330 mg/L.

Concentrations of some properties and constituents in the Chugwater aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (60 percent of samples analyzed for the property), sulfate (50 percent), filtered iron (29 percent), and manganese (20 percent).

Most available water-quality analyses for the Chugwater aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The

produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards for domestic use: TDS (100 percent), sulfate (80 percent), filtered iron (67 percent), chloride (64 percent), and pH (1 percent below lower limit and 10 percent above upper limit). TDS concentrations in 27 percent of produced-water samples from the Chugwater aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (50 percent), filtered iron (14 percent), and chloride (10 percent). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (89 percent), chloride (82 percent), sulfate (80 percent), and iron (33 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (53 percent), chloride (31 percent), sulfate (25 percent), and pH (1 percent below lower limit and 10 percent above upper limit).

7.1.11.6.2 Dinwoody confining unit

The chemical composition of groundwater in the Dinwoody confining unit in the WRB was characterized and the quality evaluated on the basis of five produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F1. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline (Appendix F1; supplementary data tables). TDS concentrations ranged from 1,540 to 14,100 mg/L, with a median of 5,320 mg/L.

Concentrations of some properties and constituents in the Dinwoody confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Chemical analyses were available for few properties and constituents; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. No concentrations were available for comparison with health-based standards (USEPA MCLs and HALs). The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), and chloride (20 percent). TDS concentrations in 20 percent of produced-water samples from the Dinwoody confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (100 percent), TDS (80 percent), and chloride (60 percent). The produced-water samples generally had concentrations of one property and two constituents that exceeded livestock-use standards: TDS (60 percent), sulfate (60 percent), and chloride (20 percent).

7.1.11.7 Recharge, discharge, and groundwater movement

Recharge to the lower and middle Mesozoic aquifers and confining units in the WRB is primarily by infiltration of precipitation and streamflow on outcrops (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). Richter (1981, p. 74) noted that "excellent recharge potential to the Cloverly aquifer exists along the Wind River Range," and that several major perennial streams (Wind, Little Wind, and Popo Agie Rivers, and Beaver and Sage Creeks) flow across outcrops of the Cloverly Formation in that area. Richter (1981, p. 77) also noted that "excellent recharge potential exists in the southwestern part" of the WRB where several major perennial streams (Little Popo Agie River, Popo Agie River, and Beaver Creek) flow across several miles of outcrop of the Frontier Formation. In the subsurface, interformational flow also may contribute to aquifer recharge (McGreevy et al., 1969; Richter, 1981).

Discharge is both natural and anthropogenic. Groundwater naturally discharges from the lower and middle Mesozoic aquifers and confining units through seeps, springs, interformational movement, and gaining streams (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). Some discharge from springs results from erosional downcutting of aquifers by streams (McGreevy et al., 1969). Richter (1981, p. 76) noted numerous springs (generally discharging less than 25 gal/min), many of which are controlled by faults and fractures, discharging from the Frontier aquifer along the Wind River Range. The primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are oil and gas wells.
No potentiometric-surface maps have been constructed for any of the hydrogeologic units included in the lower and middle Mesozoic aquifers and confining units; however, Richter (1981, p. 91-93) examined generalized regional groundwater movement in the "Lower Cretaceous rocks" of the WRB. Using potentiometric indicators such as static water levels, altitudes of springs, and petroleum drill-stem tests, he concluded that water movement in these units is generally basinward (Richter, 1981, Figure 5-1).

7.1.12 Goose Egg–Phosphoria aquifer and confining unit

The physical and chemical characteristics of the Goose Egg–Phosphoria aquifer and confining unit in the WRB are described in this section of the report.

Physical characteristics

The Goose Egg–Phosphoria aquifer and confining unit is composed of the Lower Triassic and Permian-age Goose Egg Formation and the Permian-age Phosphoria and Park City Formations **(Plate II)**. The hydrogeologic unit is overlain by the Dinwoody or Chugwater Formation and underlain by the Tensleep Sandstone. The relation between the formations composing the hydrogeologic unit is complex (Blackwelder, 1911, 1918; Condit, 1924; Thomas, 1934; Burk and Thomas, 1956; McKelvey et al., 1956; Keefer and Van Lieu, 1966); as noted by Richter (1981, p. 69), "striking lithologic variations occur from west to east across the basin, causing problems with accepted nomenclature and correlation." The approach to nomenclature used herein is the same as that used by Richter (1981) – the Phosphoria Formation was assumed to be representative of the western (basin) facies, the Park City Formation was assumed to be representative of the central facies, and the Goose Egg Formation was assumed to be representative of the eastern facies of the hydrogeologic unit. The Goose Egg Formation is composed of shale, siltstone, limestone, and gypsum with a thickness ranging from 0 to 300 ft (Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein). The Phosphoria Formation is considered equivalent to the Park City Formation (Whitcomb and Lowry, 1968; Richter, 1981). The Phosphoria and Park City Formations are composed of dense interbedded dolomite, chert, limestone, siltstone, and fine-grained sandstone with a few phosphate beds or lenses and minor amounts of shale, and range in thickness from 0 to 300 ft (Whitcomb and Lowry, 1968; Richter, 1981, table IV-1, and references therein). With the exception of oil wells, very few wells are installed in the Goose Egg–Phosphoria aquifer and confining unit, and development is limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are shallow. Most information describing the formations composing the hydrogeologic unit comes from oil exploration.

The complex intertonguing and interfingering relation between carbonate facies, siltstone facies, and shale and evaporate facies in the Goose Egg–Phosphoria aquifer and confining unit creates numerous small, permeable zones that can function as individual confined aquifers (or subaquifers). Consequently, this hydrogeologic unit can be considered a sequence of rocks that functions as both aquifer (primarily sandstone sequences) and confining or leaky confining unit (siltstone, evaporite, and shale sequences) **(Plate II)**. These subaquifers may be hydraulically connected by faults and fractures (Richter, 1981). Primary permeability is generally small, but aquifer permeability may be substantially enhanced where faults and fractures are present, especially near the mountain-basin margin along the Owl Creek Mountains and Wind River Range (Whitcomb and Lowry, 1968; Richter, 1981).

Recharge to these units is likely from infiltration of precipitation and streamflow at outcrop areas and interformational flow. Discharge from these units is likely to seeps, springs, streams, and interformational movement (Whitcomb and Lowry, 1968; Richter, 1981). Well-yield and spring-discharge measurements and other hydraulic properties for the Goose Egg–Phosphoria aquifer and confining unit are summarized on **Plate IX**; most of the data are from wells or drill-stem tests associated with petroleum extraction from the Phosphoria aquifer and confining unit.

Chemical characteristics

The chemical characteristics of the Phosphoria aquifer and confining unit are described in this section of the report. Groundwater-quality samples were not available from the Goose Egg confining unit.

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from seven wells and seven springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, diagram G). TDS concentrations were variable and indicated that most waters were fresh (69 percent of samples) and the remaining waters were slightly to moderately saline (**Appendix E1; Appendix G1**, diagram G; supplementary data tables). TDS concentrations ranged from 215 to 4,030 mg/L, with a median of 812 mg/L.

The chemical composition of groundwater in the Phosphoria aquifer and confining unit also was characterized and the quality evaluated on the basis of 146 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, diagram K). TDS concentrations from produced-water samples were highly variable and ranged from fresh to briny (**Appendix F1; Appendix H1**, diagram K; supplementary data tables). TDS concentrations ranged from 372 to 155,000 mg/L, with a median of 5,810 mg/L.

Concentrations of some properties and constituents in the Phosphoria aquifer and confining unit in the WRB 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 gross alpha radioactivity and radium-226

plus radium-228 exceeded health-based standards (USEPA MCL) in one sample. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (62 percent of samples analyzed for the property), sulfate (54 percent), and fluoride (8 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (97 percent), sulfate (94 percent), chloride (60 percent), and pH (4 percent below lower limit and 8 percent above upper limit). TDS concentrations in 36 percent of produced-water samples from the Phosphoria aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Phosphoria aquifer and confining unit exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent), radium-226 plus radium-228 (100 percent), sulfate (54 percent), TDS (15 percent), and chloride (8 percent). Concentrations of one property and one constituent exceeded State of Wyoming livestock standards in one sample: gross alpha radioactivity and radium-226 plus radium-228.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (85 percent), chloride (78 percent), and sulfate (95 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (54 percent), sulfate (33 percent), chloride (28 percent), and pH (4 percent below lower limit and 8 percent above upper limit).

7.1.13 Paleozoic aquifer system

The Paleozoic aquifer system in the WRB is contained within lithostratigraphic units ranging in age from Middle Ordovician to Pennsylvanian **(Plate II)**. The Paleozoic aquifer system in the WRB defined herein is composed of five hydrogeologic units – the Tensleep aquifer, Amsden aquifer, Madison aquifer, Darby aquifer, and Bighorn aquifer **(Plate II)**. The Paleozoic aquifer system is confined above by overlying low-permeability shales and siltstones of the Goose Egg–Phosphoria aquifer and confining unit and confined below by thick, low-permeability shales of the Gallatin–Gros Ventre confining unit **(Plate II)**. The Paleozoic aquifer system is about 2,000 ft thick, and underlies the entire WRB except the Granite Mountains area (Richter, 1981). Formations composing the aquifer system crop out along the margins of the Wind River Range, Owl Creek Mountains, and Rattlesnake Hills **(Plate I)**.

The Paleozoic aquifer system includes some of the most important aquifers in the WRB. Depending on location and depth, wells completed in the aquifers produce highly variable quantities and qualities of water. Except near outcrops, where water-table (unconfined) conditions may occur, groundwater in the Paleozoic aquifer system generally is semi-confined or confined. With the exception of wells utilized for oil and gas production, most wells completed in the Paleozoic aquifer system in the WRB are located in or near outcrops along basin margins or along basin margins where drilling depths are shallow and economical.

Permeability in the Paleozoic aquifer system aquifers is controlled by lithology, sedimentary structure and depositional environment, and tectonic structure (Richter, 1981). The predominant lithologies of the lithostratigraphic units composing the aquifer system are sandstone, carbonates (limestone and dolomite), and shale. Primary porosity and intergranular permeability are much greater in the sandstones than in the carbonates and shale, where primary permeability is very low (Richter, 1981). Carbonate aquifers generally are only utilized in areas where substantial secondary permeability is developed, most commonly in areas of structural deformation (for example, anticlines) and its associated faults and fractures.

The Tensleep and Madison aquifers are the most productive (permeable) aquifers in the Paleozoic aquifer system; consequently, both aquifers are utilized substantially more than the Amsden, Darby, and Bighorn aquifers (Richter, 1981). In fact, relatively few wells are completed in the Amsden, Darby, and Bighorn aquifers because of their lower primary permeability. The Tensleep and Madison aquifers are considered "major" or "principal" aquifers because wells at some locations yield hundreds of gallons per minute. Thus, the aquifers can be developed for domestic, public supply, or stock use at some locations in the WRB, where groundwater quality is acceptable for these uses. Both aquifers also are extensively utilized for oil and gas production in the basin.

The groundwater quality of aquifers in the Paleozoic aquifer system varies greatly throughout the WRB. Recharge to the aquifer system generally occurs where the formations crop out near basin margins. Near recharge areas, water in the aquifer system may be relatively fresh and suitable for most uses. This is where most domestic, public-supply, or stock wells are completed. Elsewhere, and with increasing depth (as indicated primarily by produced-water samples) and as the water moves away from outcrops into the basin interior, the water may have large TDS concentrations (be highly mineralized) and be unsuitable for most uses or only marginally suitable for livestock and other uses. Only oil or gas wells are completed in

deeply buried Paleozoic stratigraphic units.

7.1.13.1 Tensleep aquifer

The physical and chemical characteristics of the Tensleep aquifer in the WRB are described in this section of the report.

Physical characteristics

The Tensleep aquifer is a major aquifer in the WRB. The Middle and Upper Pennsylvanian-age Tensleep Sandstone comprises the Tensleep aquifer in the WRB **(Plate II)**. The Tensleep aquifer is composed of predominantly tan, massive to cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica (Todd, 1963; Keefer and Van Lieu, 1966; Richter, 1981; Love et al., 1993). Irregular chert layers and thin limestones and dolomites also are present (Richter, 1981). Reported thickness of the hydrogeologic unit in the WRB ranges from 200 to 600 ft (Richter, 1981, table IV-1). The Tensleep aquifer is the uppermost hydrogeologic unit of the Paleozoic aquifer system. The Tensleep Sandstone is overlain by the Phosphoria or Goose Egg Formations and underlain by the Amsden Formation **(Plate II)**. No regional confining unit separates the Tensleep aquifer from the underlying Amsden aquifer.

The Tensleep aquifer is used primarily as a source of water for domestic, public-supply, industrial, and (rarely) irrigation purposes (Plafcan et al., 1995). The Tensleep aquifer is productive throughout the WRB; and, on the basis of well yields, the uppermost 200 ft of the aquifer is the most productive (Richter, 1981). Hydrogeologic data describing the Tensleep aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**. Spring and well yields and transmissivities from the Tensleep aquifer compiled for this study **(Plate IX)** indicate that it is one of the most productive hydrogeologic units in the Wind River Basin. In fact, the median spring and well yield (67.5 gal/min) is second only to that of the Madison aquifer among lithostratigraphic units in the WRB **(Plate IX)**. Most wells completed in the Tensleep aquifer are located along the basin margin where the Tensleep Sandstone crops out or is present at shallow depth. Many wells flow at land surface due to artesian pressure. Large volumes of water are withdrawn from the numerous oilfields in the basin.

On the basis of studies conducted in the Bighorn Basin, porosity and permeability in the Tensleep aquifer is thought to be primarily intergranular and to depend on the amount of secondary cementation and re-crystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966). Emmett et al. (1971) noted that highly crossbedded sandstones had lower permeabilities than regular bedded sandstones. Fractures and solution processes (in carbonate-rich zones) may enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976; Richter, 1981). Secondary fracture porosity and permeability is common in folds and faults that deform the Tensleep Sandstone, and these locations, as reported in numerous studies in the Bighorn Basin, have the best potential for groundwater development (Western Water Consultants, Inc., 1982a,b; Jarvis, 1986a; Spencer, 1986a); by inference, the same potential likely exists in the WRB as well. In fact, Whitcomb and Lowry (1968) noted that the most productive wells in the Tensleep aquifer are associated with local structures where fracturing has increased permeability, and Richter (1981) noted that permeability in highly fractured parts of the aquifer along the Wind River Range might be several orders of magnitude greater than permeability in relatively undeformed areas such as the central WRB.

Chemical characteristics

The chemical composition of groundwater in the Tensleep aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 14 wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, diagram H). TDS concentrations were variable and indicated that most waters were fresh (93 percent of samples) and the remaining waters were slightly saline (**Appendix E1**; **Appendix G1**, diagram H; supplementary data tables). TDS concentrations ranged from 146 to 1,060 mg/L, with a median of 208 mg/L.

The chemical composition of groundwater in the Tensleep aquifer also was characterized and the quality evaluated on the basis of 114 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, diagram L). TDS concentrations from produced-water samples were highly variable, ranging from fresh to very saline (**Appendix F1; Appendix H1**, diagram L; supplementary data tables). TDS concentrations ranged from 167 to 25,600 mg/L, with a median of 2,930 mg/L.

Concentrations of some properties and constituents in the Tensleep aquifer in the WRB 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 property and two constituents commonly exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), gross alpha radioactivity (50 percent), and radium-226 plus radium-228 (33 percent). Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (13 percent) and sulfate (7 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (100 percent), TDS (95 percent), sulfate (94 percent), chloride (40 percent), and pH (2 percent below lower limit and 8 percent above upper limit). TDS concentrations in 11 percent of produced-water samples from the Tensleep aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Tensleep aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (50 percent), radium-226 plus radium-228 (33 percent), and sulfate (7 percent). Concentrations of one property and one constituent exceeded State of Wyoming livestock standards: gross alpha radioactivity (50 percent) and radium-226 plus radium-228 (33 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (95 percent), TDS (83 percent), and chloride (77 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (19 percent), chloride (9 percent), sulfate (9 percent), and pH (2 percent below lower limit and 8 percent above upper limit).

7.1.13.2 Amsden aquifer

The physical and chemical characteristics of the Amsden aquifer in the WRB are described in this section of the report.

Physical characteristics

The permeable parts of the Lower Pennsylvanian- and Upper Mississippian-age Amsden Formation compose the Amsden aquifer in the WRB (**Plate II**; Richter, 1981). The Amsden aquifer is part of the Paleozoic aquifer system. The Amsden Formation is overlain by the Tensleep Sandstone and underlain by the Madison Limestone **(Plate II)**. The Amsden Formation is composed of two stratigraphic sequences—a complex upper sequence of "nonresistant shale, dense dolomite, thin cherty limestone, and thin, resistant, fine-grained sandstone," and the basal Darwin Sandstone Member, composed of a "fine- to medium-grained, cross-bedded to massive, friable, porous sandstone" (Richter, 1981, table IV-1, from Keefer and Van Lieu, 1966). Reported thickness of the Amsden Formation ranges from 0 to 400 ft in the WRB (Richter, 1981, table IV-1). Permeability in the Darwin Sandstone is attributed to joints and partings between bedding planes, whereas permeability of both the upper and basal sequences may be substantially enhanced where fractured (Richter, 1981). Essentially no development of the aquifer has occurred because higher yields can be obtained from wells completed in other aquifers within the Paleozoic aquifer system, commonly at shallower depth. Consequently, almost no study of the aquifer has occurred, and the little quantitative hydrogeologic information that could be located for the Amsden aquifer in the WRB is presented on **Plate IX**.

The water-bearing potential of the Amsden aquifer near Lander was briefly mentioned by Weston Engineering, Inc. (2004a; 2004b, p. IV-1). The investigators noted "tightness" and little water production when attempting to drill through the Amsden Formation to reach the underlying Madison aquifer.

Chemical characteristics

The chemical composition of groundwater in the Amsden aquifer in the WRB was characterized and the quality evaluated on the basis of one produced-water sample. Individual constituent concentrations are listed in **Appendix F1**. The TDS concentration (6,100 mg/L) indicated that the water was moderately saline. Health-based standards (USEPA MCLs and HALs) were not applicable for any of the constituents analyzed for in the produced-water sample. Concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs) for domestic use, as well as standards for agricultural use. Concentrations of TDS and sulfate also exceeded livestock-use standards.

7.1.13.3 Madison aquifer

The physical and chemical characteristics of the Madison aquifer in the WRB are described in this section of the report.

Physical characteristics

The Madison aquifer is a major aquifer in the WRB. The permeable parts of the Lower and Upper Mississippian-age Madison Limestone compose the Madison aquifer in the WRB **(Plate II)**. The Madison Limestone is composed of two stratigraphic members – an upper member, about 100 ft thick, consisting of thin to massive, irregularly bedded, gray to tan limestone and dolomite, and a lower member, about 500 to 600 ft thick, consisting of predominantly bluish-gray to gray, massive to thin-bedded, crystalline limestone and dolomitic limestone (Keefer and Van Lieu, 1966). The Madison Limestone is overlain by the Amsden Formation and underlain by the Darby Formation **(Plate II)**. No regional confining units separate the Madison aquifer from the Amsden and Darby aquifers. The Madison Limestone is locally cavernous in outcrop areas.

Permeability in the Madison aquifer is primarily secondary and is attributed to solution-enhanced fractures, joints, and caverns (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Primary permeability is very low to nonexistent because of the dense and finely crystalline structure of the carbonates composing the aquifer (Richter, 1981). Without development of secondary permeability, well yields in the Madison aquifer are likely to be relatively small (for example, see results of exploratory drilling in Wyoming Water Development Commission, 1996). The most productive (permeable) parts of the Madison aquifer are areas with substantial fractures and cavernous zones (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Jorgensen Engineering and Land Surveying, 1995). Richter noted that most cavern development is in the upper one-third of the Madison Limestone.

The Madison aquifer is used as a source of water for domestic, commercial, stock, public supply, industrial, and (rarely) irrigation purposes (Plafcan et al., 1995). The aquifer is highly productive. Hydrogeologic data describing the Madison aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**. Spring and well yields and transmissivities from the Madison aquifer compiled for this study **(Plate IX)** indicate that it is the most productive hydrogeologic unit in the Wind River Basin. In fact, the median spring and well yield (90 gal/min) is the highest calculated for lithostratigraphic units in the WRB **(Plate IX)**. Most wells completed in the Madison aquifer are located along the basin margin where the Madison Limestone crops out or is present at relatively shallow depth. Water in the aquifer is generally confined, and most wells flow at land surface due to artesian pressure. Large volumes of water also are withdrawn from the numerous oil fields in the Wind River Basin.

Chemical characteristics

The chemical composition of groundwater in the Madison aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from nine wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix E1; Appendix G1**, diagram I). TDS concentrations indicated that the waters were fresh. TDS concentrations ranged from 181 to 920 mg/L, with a median of 216 mg/L.

The chemical composition of groundwater in the Madison aquifer also was characterized and the quality evaluated on the basis of 64 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations from produced-water samples were highly variable and ranged from fresh to very saline, but most were slightly saline (70 percent) (**Appendix F1; Appendix H1**, diagram M; supplementary data tables). TDS concentrations ranged from 291 to 30,600 mg/L, with a median of 2,040 mg/L.

Concentrations of some properties and constituents in the Madison aquifer in the WRB 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 (USEPA MCLs and HALs): arsenic (17 percent of samples analyzed for the constituent) and radium-226 plus radium-228 (17 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (29 percent), TDS (15 percent), filtered iron (14 percent), and sulfate (8 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. In the one produced-water sample analyzed for arsenic, the arsenic concentration exceeded the health-based standard (USEPA MCL). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (98 percent), sulfate (98 percent), chloride (73 percent), filtered iron (25 percent), manganese (20 percent), and pH (3 percent below lower limit and 3 percent above upper limit). TDS concentrations in 8 percent of produced-water samples from the Madison aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Constituents in environmental water samples that had concentrations greater than agricultural-use standards were radium-226 plus radium-228 (17 percent) and sulfate (8 percent). Concentrations of one constituent exceeded State of Wyoming livestock standards: radium-226 plus radium-228 (17 percent).

The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded agricultural-use standards: arsenic (100 percent), sulfate (98 percent), TDS (53 percent), and chloride (92 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: arsenic (100 percent), TDS (16 percent), chloride (14 percent), pH (3 percent below lower limit and 3 percent above upper limit), and sulfate (2 percent).

7.1.13.4 Darby aquifer

The permeable parts of the Upper Devonian-age Darby Formation compose the Darby aquifer in the WRB **(Plate II)**. The Darby Formation, present only in the western WRB, is composed of resistant dolomite, siltstone, and shale (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Reported thickness of the Darby Formation ranges from 0 to 200 ft (Keefer, and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Darby Formation likely functions as an aquifer only in areas with substantial secondary permeability (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Richter (1981, table IV-1, p. 52) noted that the formation could be "generally considered a confining unit, but permeable along joints and fractures." Nonetheless, Richter classified the formation as an aquifer, and that classification has been utilized by subsequent investigators and is retained herein. Joints in the aquifer provide small quantities of water (generally less than 10 gal/min) to numerous springs along the Wind River Range (Richter, 1981, table IV-1, p. 52). The Darby aquifer is part of the Paleozoic aquifer system. The Darby Formation is overlain by the Madison Limestone and underlain by the Bighorn Dolomite **(Plate II)**. No regional confining units separate the Darby aquifer from the Madison and Bighorn aquifers. Essentially no quantitative hydrogeologic information is available describing the physical or chemical characteristics of the Darby aquifer in the WRB because few, if any, wells are completed in the aquifer.

7.1.13.5 Bighorn aquifer

The physical and chemical characteristics of the Bighorn aquifer in the WRB are described in this section of the report.

Physical characteristics

The permeable parts of the Middle and Upper Ordovician-age Bighorn Dolomite compose the Bighorn aquifer in the WRB **(Plate II)**. The Bighorn Dolomite is composed of two stratigraphic sequences – the upper Leigh Dolomite Member composed of dense, thin-bedded to massive dolomite and the basal Lander Sandstone Member, composed of fine- to medium-grained sandstone (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Reported thickness of the Bighorn Dolomite ranges from 0 to 300 ft (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Permeability in the basal Lander Sandstone Member likely is both primary (intergranular) and secondary (joints and fractures), whereas permeability in the upper Leigh Dolomite Member is secondary (joints and fractures) (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Joints in the aquifer provide small quantities of water (generally less than 10 gal/min) to numerous springs along the Wind River Range (Richter, 1981, table IV-1, p. 52 and p. 68). The Bighorn aquifer is the basal hydrogeologic unit of the Paleozoic aquifer system. The Bighorn Dolomite is overlain by the Darby Formation and underlain by the regionally extensive Gallatin Limestone **(Plate II)**. Little quantitative hydrogeologic information is available describing the physical or chemical characteristics of the Bighorn aquifer in the WRB because few wells are completed in the aquifer, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Bighorn aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in Appendix E1. TDS concentrations indicated that waters were fresh. TDS concentrations ranged from 102 to 222 mg/L, with a median of 178 mg/L. On the basis of the few properties and constituents analyzed for in the three spring samples, waters were likely suitable for most uses as no properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.1.13.6 Groundwater recharge, discharge, and movement

Aquifers in the Paleozoic aquifer system are recharged primarily from precipitation (rain and snow melt) and streamflow infiltrating outcrops along mountain-basin margins (Whitcomb and Lowry, 1968; Richter, 1981; Jorgensen Engineering and Land Surveying, 1993a,b). Richter (1981, p. 69) reported that "excellent recharge potential exists along the elevated flanks of the Wind River and Owl Creek Mountains, where annual precipitation exceeds 60 inches per year and numerous perennial streams flow across outcrops." Substantial streamflow losses may occur where streams cross karstic Paleozoic-age rocks. In Sinks Canyon, west of Lander along the flanks of the Wind River Range, the Middle Popo Agie River loses all flow to the karstic Madison Limestone as it flows across the outcrop; flow reappears about one-half mile downstream (Whitcomb and Lowry, 1968).

Discharge from aquifers of the Paleozoic aquifer system is both natural and anthropogenic. Richter (1981) reported small spring flows (generally less than 10 gal/min) from Paleozoic aquifers along the Wind River Range. Other sources of natural discharge from aquifers in the Paleozoic aquifer system include numerous springs, gaining streams, and other aquifers. Some springs discharge thermal waters (Breckenridge and Hinckley, 1978; Hinckley et al., 1982a,b; Hinckley and Heasler, 1987). Large thermal springs from the Madison aquifer and adjacent aquifers in the Paleozoic aquifer system discharge at the mouths of the canyons of Warm Spring Creek and Little Warm Spring Creek near Dubois (Breckenridge and Hinckley, 1978; Hinckley et al., 1982a,b; Hinckley and Heasler, 1987; Jorgensen Engineering and Land Surveying, 1995). The

primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are large-capacity public-supply, irrigation, and oil and gas wells (Whitcomb and Lowry, 1968; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). No potentiometric-surface maps have been constructed showing groundwater flow in aquifers of the Paleozoic aquifer system.

7.1.14 Gallatin–Gros Ventre confining unit

The physical and chemical characteristics of the Gallatin–Gros Ventre confining unit in the WRB are described in this section of the report.

Physical characteristics

The Gallatin–Gros Ventre confining unit is composed of the Cambrian-age Gallatin Limestone and Gros Ventre Formation. The thick unit confines and separates the underlying Flathead aquifer from the overlying Paleozoic aquifer system **(Plate II)**. Reported thickness of the Gallatin Limestone ranges from 0 to about 450 ft, and the thickness of the Gros Ventre Formation ranges from 0 to about 700 ft (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Gallatin Limestone is composed of dense, thinly bedded to massive, glauconitic and oolitic limestone with interbedded shale, silty shale, and thin sandstone beds (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Gros Ventre Formation is composed of limestone, shale, calcareous shale, and a basal flat-pebble conglomerate (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Even though both formations are considered to be confining units, both may yield small quantities of water to wells and springs at some locations in the WRB, especially areas with secondary permeability attributable to joints and fractures (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981, table IV-1). Joints in the hydrogeologic unit provide small quantities of water (generally less than 5 gal/min) to springs along the Wind River Range (Richter, 1981, table IV-1, p. 53). Little hydrogeologic information is available describing the Gallatin–Gros Ventre confining unit, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Gallatin confining unit in the WRB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (296 mg/L) indicated that the water was fresh (**Appendix E1**; supplementary data tables). On the basis of the few properties and constituents analyzed for in the one sample, the water was likely suitable for most uses as no concentrations of properties or constituents in water from the Gallatin confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.1.15 Flathead aquifer

The physical and chemical characteristics of the Flathead aquifer in the WRB are described in this section of the report.

Physical characteristics

The Flathead aquifer is composed of the Cambrian-age Flathead Sandstone **(Plate II)**. The Flathead aquifer is a major aquifer in the WRB. The Flathead Sandstone consists of pink, reddish-brown, tan and gray, fine- to medium-grained, arkosic and quartzitic sandstone, with some conglomerate and arkose in the lower part (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Flathead aquifer is confined by the overlying Gallatin–Gros Ventre confining unit and below by nonporous igneous and metamorphic rocks of the Precambrian basement that act as a basal confining unit to all aquifers and aquifer systems in the WRB **(Plate II)**.

The Flathead Sandstone is present throughout the WRB and ranges from 50 to 200 ft in thickness (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Water in the Flathead aquifer is semi-confined to confined and likely is under high artesian pressures (Richter, 1981). Shut-in wellhead pressure from an exploratory well in the Lander area was estimated to be as great as 525 psi (Weston Engineering, Inc., 2007b). Porosity is intergranular, but secondary permeability is present along partings between bedding planes and as fractures associated with folds and faults (Richter, 1981, table IV-1). Recharge to the Flathead aquifer likely is from infiltration of precipitation and streamflow losses in outcrop areas. Little hydrogeologic information is available describing the Flathead aquifer, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**. Although considered a potentially very good source of groundwater for development by many investigators, the aquifer is essentially undeveloped as a source of water because of deep burial throughout most of the WRB and the availability of shallower aquifers.

Chemical characteristics

The chemical composition of groundwater in the Flathead Sandstone in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations (37 and 228 mg/L) indicated that the waters were fresh. On the basis of the few properties and constituents analyzed in the two spring samples, the quality of water from the Flathead Sandstone in the WRB is likely suitable for most uses. None of the concentrations of properties or constituents in water from the Flathead aquifer approached or exceeded applicable USEPA or State

of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Flathead aquifer in the WRB also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (2,590 mg/L) indicated that the water was slightly saline. Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in the produced-water sample and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Flathead aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the constituents analyzed had applicable health-based standards; however, concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs) for domestic use and exceeded State of Wyoming agricultural-use standards. No concentrations of properties or constituents exceeded State of Wyoming livestock standards.

7.1.16 Precambrian basal confining unit

The physical and chemical characteristics of the Precambrian basal confining unit in the WRB are described in this section of the report.

Physical characteristics

Undifferentiated nonporous igneous and metamorphic rocks of the Precambrian basement act as a basal confining unit for the Flathead aquifer, as well as for all aquifers and aquifer systems in the WRB **(Plate II)**. Little is known about Precambrian rocks at depth in the WRB; however, wells have been completed locally in this hydrogeologic unit for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out – permeability is attributable to weathered, jointed, fractured, or faulted rocks (Whitcomb and Lowry, 1968; Richter, 1981). Little hydrogeologic information is available for the Precambrian basal confining unit, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Precambrian basal confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations (108 and 187 mg/L) indicated that the waters were fresh. On the basis of the few properties and constituents analyzed for in the two spring samples, the quality of water from the Precambrian basal confining unit in the WRB is likely suitable for most uses. No concentrations of properties or constituents in water from the Precambrian basal confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2 Bighorn Basin

The physical and chemical characteristics of hydrogeologic units in the Bighorn Basin (BHB) are described in this section of the report. These hydrogeologic units are identified on **Plate III**.

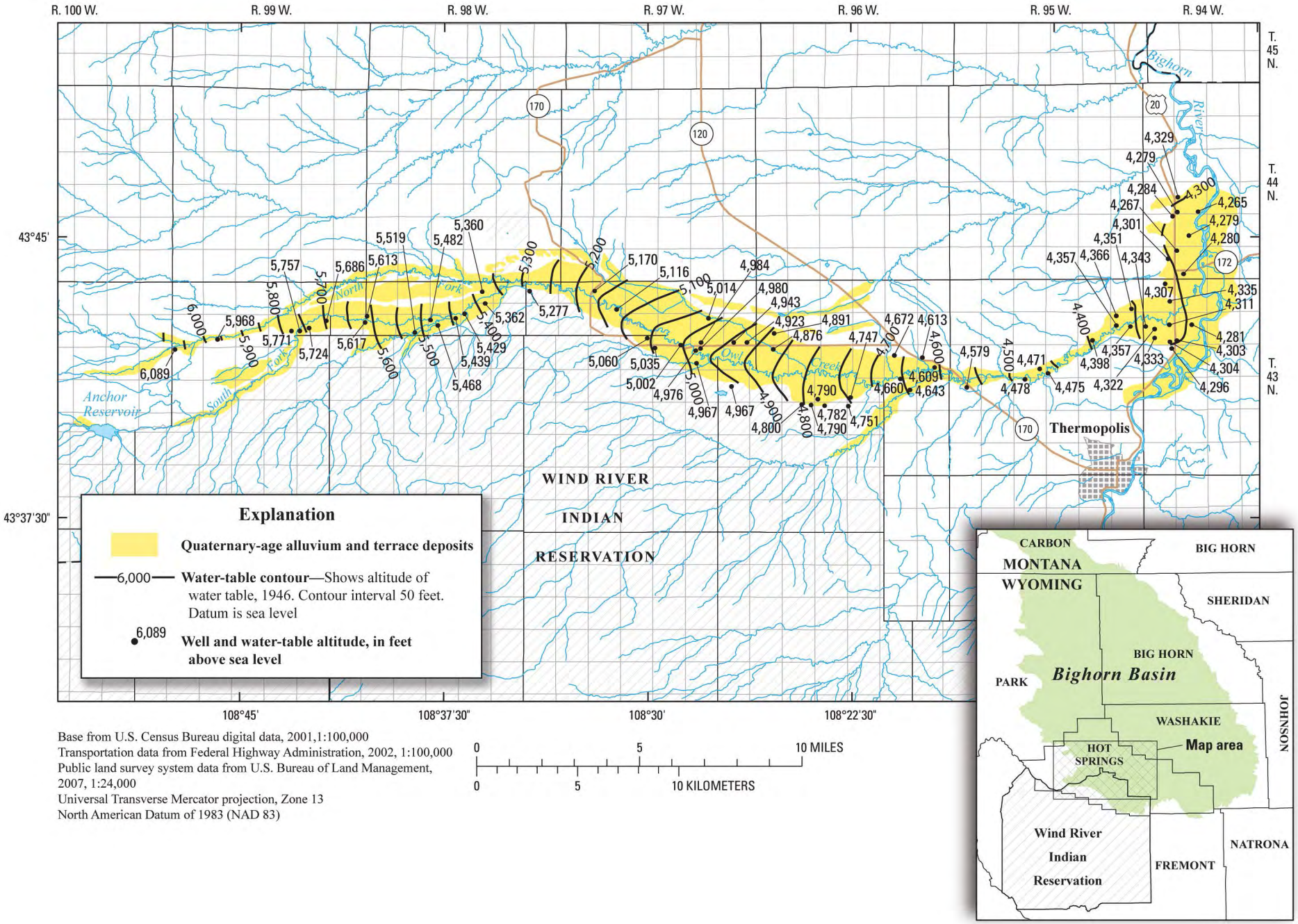
7.2.1 Quaternary unconsolidated-deposit aquifers

The physical and chemical characteristics of the Quaternary unconsolidated-deposit aquifers in the BHB are described in this section of the report. Much of the description of the physical characteristics of these aquifers was modified from Bartos et al. (2005).

Physical characteristics

Unconsolidated deposits of Quaternary age contain aquifers (referred to herein as "Quaternary unconsolidated-deposit aquifers") that can be highly productive locally and are the source of water for many shallow wells in the BHB. Quaternary unconsolidated-deposit aquifers are widely used sources of water for domestic, stock, irrigation, or public-supply purposes.

Quaternary unconsolidated-deposit aquifers 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 (Swenson, 1957; Robinove and Langford, 1963; Lowry et al., 1976; Cooley and Head, 1979a,b, 1982; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). These aquifers have small areal extent and primarily occur as alluvium (commonly associated with colluvium and referred to as "alluvial aquifers") or terrace deposits (sometimes referred to as "gravel, pediment, and sand deposits" in some reports and referred to herein as "terrace-deposit aquifers") along narrow valleys and in adjacent upland areas, and along streams and rivers in the BHB **(Plates I and III)**. Consequently, many wells completed in Quaternary unconsolidated-deposit aquifers are located close to and along streams and rivers because deposits commonly are less than 1 mile wide near streams in the basin. Along the floodplains, wells completed in alluvial aquifers are likely in hydraulic connection with streams and rivers. Some Quaternary unconsolidated-deposit aquifers are composed of saturated landslide and glacial deposits (Lowry et al., 1976; Libra et al., 1981). Terrace deposits of the BHB are present in many different terrace levels alongside rivers draining the basin



Base from U.S. Census Bureau digital data, 2001,1:100,000
Transportation data from Federal Highway Administration, 2002, 1:100,000
Public land survey system data from U.S. Bureau of Land Management, 2007, 1:24,000
Universal Transverse Mercator projection, Zone 13
North American Datum of 1983 (NAD 83)

0 5 10 MILES
0 5 10 KILOMETERS

Figure 7-5. Water-table contours in Quaternary unconsolidated-deposit aquifers in Owl Creek Valley, Wyoming (modified from Berry and Littleton, 1961, Plate II).

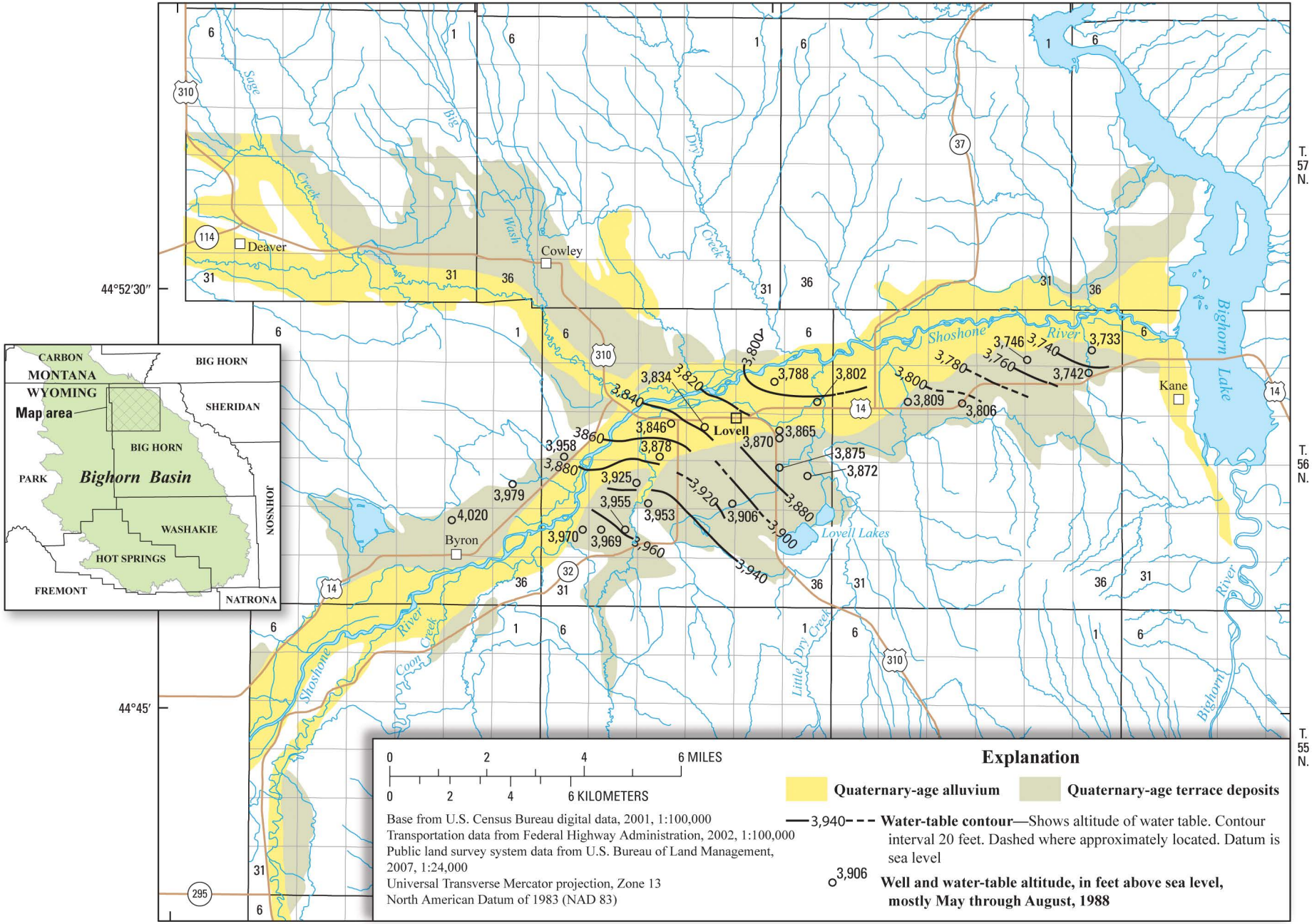


Figure 7-6. Water-table contours in Quaternary alluvial and terrace-deposit aquifers along the Shoshone River, Wyoming (modified from Plafcan et al., 1993, Figure 9).

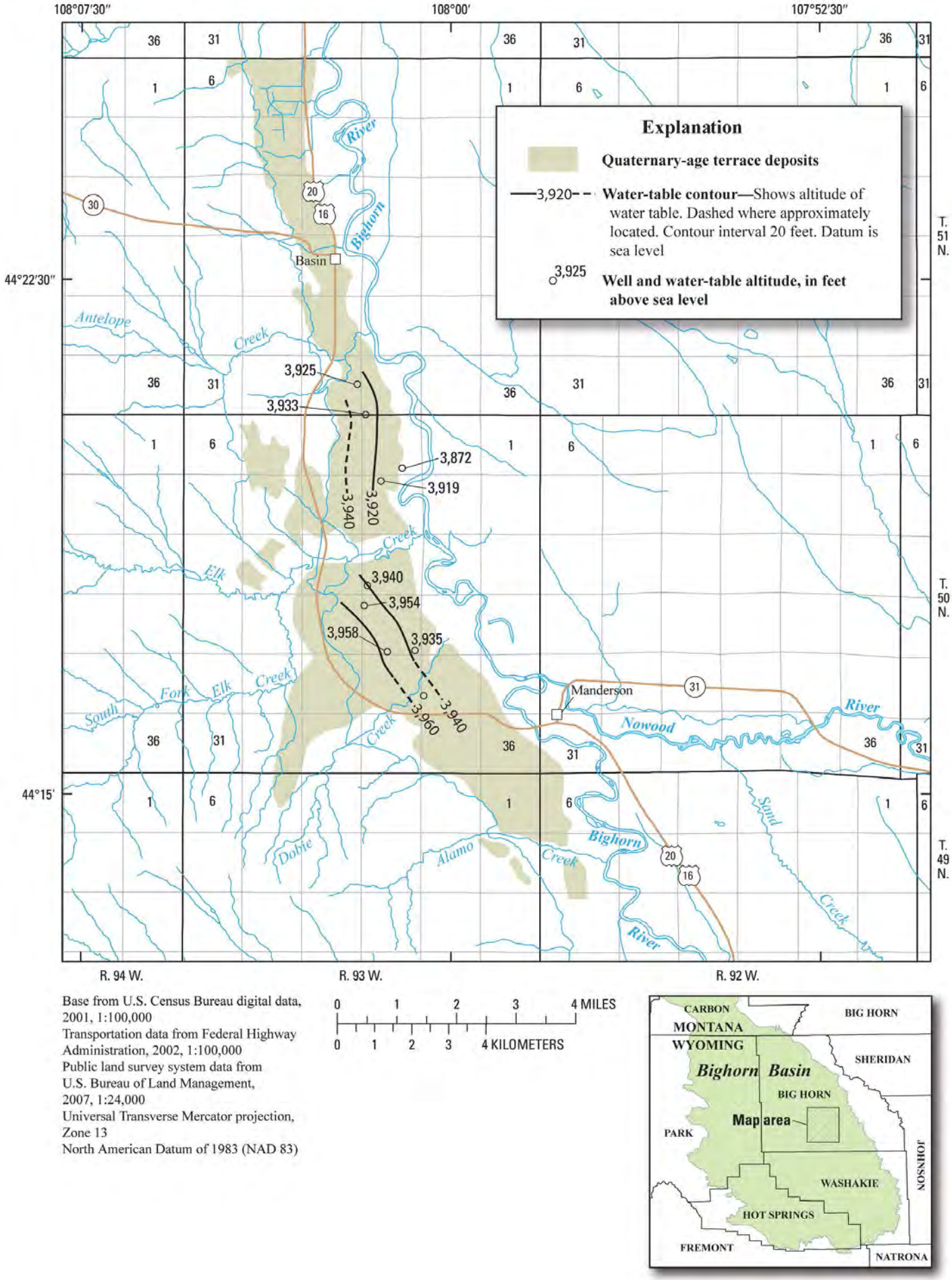


Figure 7-7. Water-table contours in Quaternary terrace-deposit aquifers along Orchard Bench, Wyoming (modified from Plafcan et al., 1993, Figure 10).

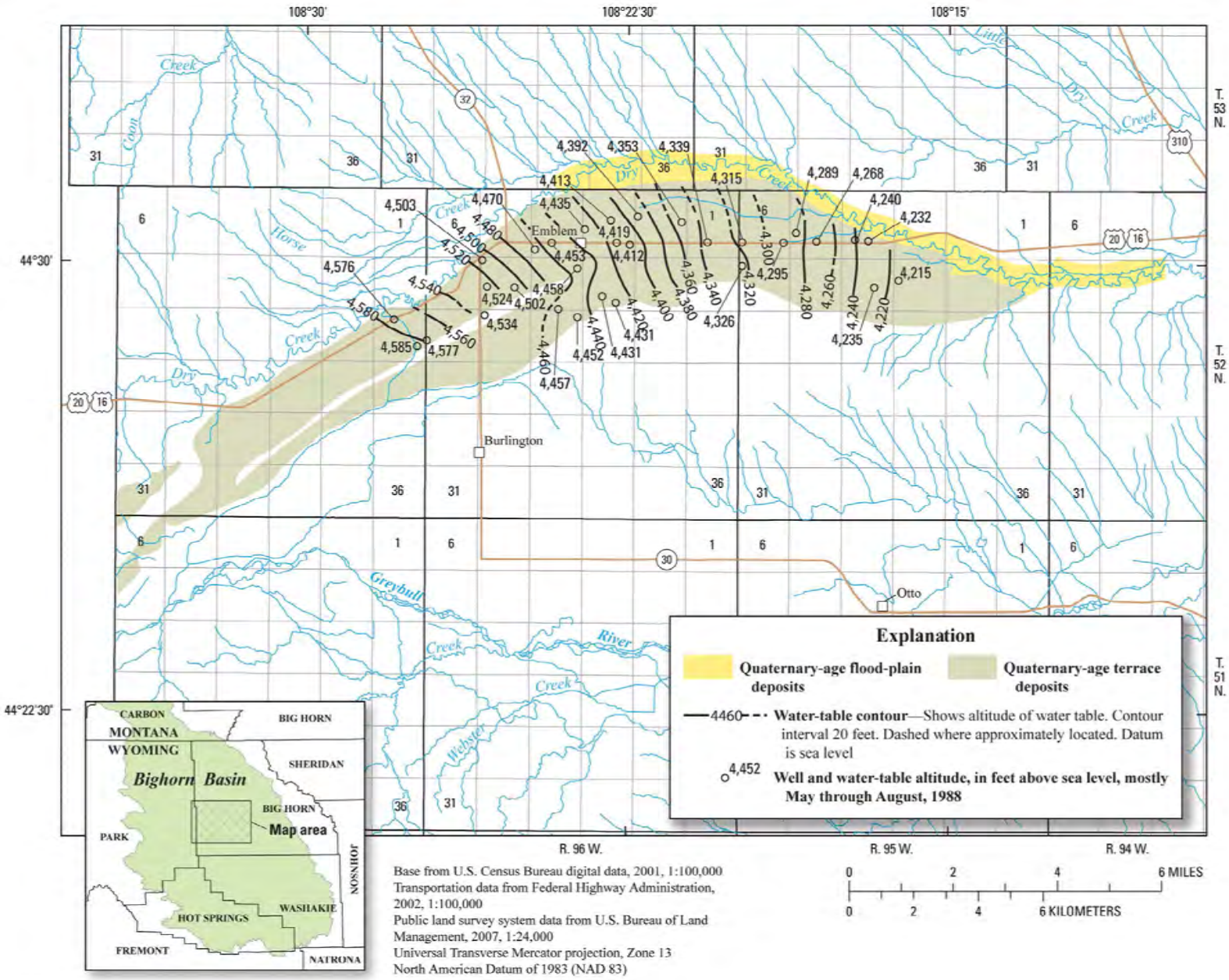
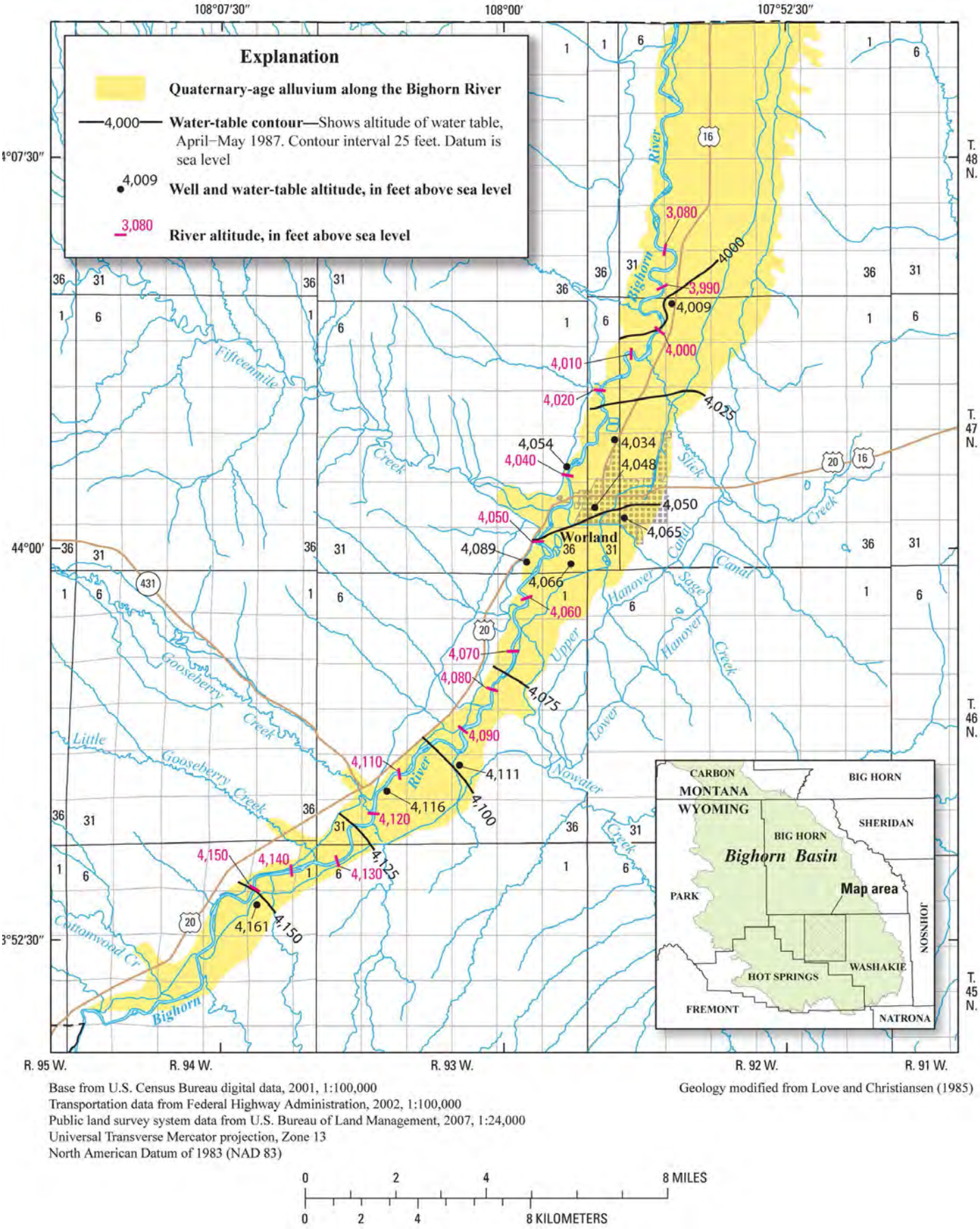


Figure 7-8. Water-table contours in Quaternary terrace-deposit aquifers along Emblem Bench, Wyoming (modified from Plafcan et al., 1993, Figure 11).



Base from U.S. Census Bureau digital data, 2001, 1:100,000
Transportation data from Federal Highway Administration, 2002, 1:100,000
Public land survey system data from U.S. Bureau of Land Management, 2007, 1:24,000
Universal Transverse Mercator projection, Zone 13
North American Datum of 1983 (NAD 83)

Geology modified from Love and Christiansen (1985)

0 2 4 8 MILES
0 2 4 8 KILOMETERS

Figure 7-9. Water-table contours in Quaternary alluvial aquifers along the Bighorn River, Wyoming (modified from Susong et al., 1993, Figure 8).

and in adjacent upland areas. The terrace sequence in the BHB has been studied by many investigators because the sequence is considered to be a model of late Cenozoic erosional history as well as a model of the fluvial history and mechanics of basin rivers (Mackin, 1937, 1947; Moss and Bonini, 1961; Ritter, 1967, 1975; Palmquist, 1978, 1979, 1983; Reheis, 1982; Ritter and Kauffman, 1983).

The thickness of alluvium and terrace deposits in the BHB varies substantially, depending on stream or river valley and location; thickness may be as great as 100 ft, but the thickness of alluvium generally is less than 30 ft and the thickness of terrace deposits generally is less than 50 ft (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976, and references therein; Cooley and Head, 1979a,b, 1982; Libra et al., 1981; Western Water Consultants, Inc., 1983a; McLellan, 1988; Plafcan et al., 1993; Susong et al., 1993; Lidstone and Associates, Inc., 2007b).

Well yield from Quaternary unconsolidated-deposit aquifers varies considerably in the BHB; it is directly related to the size and sorting of material composing a deposit as well as the saturated thickness of the deposit. Well yields are high from aquifers having great saturated thickness and very-coarse grain size. Alluvium derived from mountainous areas generally is coarser than alluvium from formations in the basin (Lowry et al., 1976; Plafcan and Ogle, 1994, Table 5). Hydrogeologic data describing the Quaternary-age unconsolidated deposits (alluvial aquifers, terrace-deposit aquifers, and glacial-deposit aquifers), including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

The areal extent of Quaternary unconsolidated-deposit aquifers coincides with much of the rural population and irrigated cropland in the BHB, so these aquifers are particularly susceptible to contamination from human activities at the land surface. In fact, evidence of groundwater contamination by human activities has been detected as elevated nitrate concentrations and as organic compounds such as volatile organic compounds and pesticides (Plafcan et al., 1993; Susong et al., 1993; Eddy-Miller, 1998a,b; Eddy-Miller and Norris, 2001; Eddy-Miller and Remley, 2005; Bartos et al., 2005, 2009). In a statewide assessment of pesticides in groundwater in Wyoming, the largest percentage of pesticide detections and the largest number of different pesticides detected were in samples from wells in the BHB, many of which were completed in Quaternary unconsolidated-deposit aquifers (Bartos et al., 2009).

Recharge, discharge, and groundwater movement

Recharge to many Quaternary unconsolidated-deposit aquifers is not only from direct infiltration of precipitation and ephemeral and perennial streamflow losses, but also from infiltration of diverted surface water from unlined irrigation canals and ditches, from water applied to fields, and as discharge from underlying aquifers (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Cooley and Head, 1979a,b, 1982; Plafcan et al., 1993). Most unconsolidated terrace deposits in the BHB were not saturated prior to irrigation, indicating that recharge of diverted surface water likely is the dominant source of recharge to terrace-deposit aquifers (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963). Water levels in many terrace-deposit aquifers are directly related to irrigation diversions. During the irrigation season, water levels in these deposits at some locations are the same elevation as water levels in unlined irrigation canals and ditches (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Plafcan et al., 1993). Water levels in terrace-deposit aquifers typically begin to rise some time after irrigation begins (generally March to April in the BHB), continue to rise after irrigation ceases as surface soils continue to drain (generally September to October), and reach maximum water levels in early winter (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Plafcan et al., 1993). Consequently, water quality in these terrace-deposit aquifers is likely to vary during the year in response to application of diverted surface water, variation in surface-water quality throughout the irrigation season, and subsequent infiltration and percolation of these waters (Plafcan et al., 1993).

Discharge from Quaternary unconsolidated-deposit aquifers occurs by evapotranspiration, gaining streams, seeps, drains, and spring flows, as well as withdrawals from wells and collection galleries (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). Evapotranspiration from Quaternary unconsolidated-deposit aquifers is likely to be highest in areas where crops are grown (Libra et al., 1981).

Groundwater flow in most Quaternary unconsolidated-deposit aquifers generally is toward rivers or in the direction of streamflow (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). Robinove and Langford (1963) reported that that the Greybull River is a gaining stream throughout most of its length. A water-table contour map constructed by Berry and Littleton (1961, Figure 8) indicates that groundwater in the Quaternary unconsolidated-deposit aquifers along the Owl Creek Valley flows toward the river in the direction of streamflow **(Figure 7-5)**. The investigators also noted that the slope of the water table was nearly the same as that of the stream channel (75 feet per mile in the western part and about 30 feet per mile in eastern

part), and that Owl Creek generally is a gaining stream but is a losing stream near its confluence with the Bighorn River. A water-table contour map constructed by Plafcan et al. (1993, **Figure 9**) indicates that groundwater in the alluvial aquifers along the Shoshone River near Lovell in Big Horn County flows toward the river, and groundwater in the terrace-deposit aquifers in the same area generally flows in the downstream direction or toward the river **(Figure 7-6)**. Water-table contour maps constructed by Plafcan et al. (1993, **Figures 10 and 11**) indicate that groundwater in the terrace-deposit aquifers along Orchard Bench **(Figure 7-7)** and Emblem Bench **(Figure 7-8)** in Big Horn County generally flows in the downstream direction or toward the river. A water-table contour map constructed by Susong et al. (1993, Figure 8) indicates that groundwater in alluvial aquifers along the Bighorn River flows toward the river in Washakie County **(Figure 7-9)**.

Chemical characteristics

The chemical composition of groundwater from alluvial and terrace-deposit aquifers is evaluated in this section of the report.

Alluvial aquifers

The chemical composition of groundwater in alluvial aquifers in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 109 wells and 3 springs. Summary statistics calculated for available constituents are listed in Appendix E2. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram A). TDS concentrations were highly variable and indicated that about one-half of waters were slightly saline (51 percent), slightly less than one-half of waters were fresh (46 percent), and the remaining waters were moderately saline (**Appendix E2; Appendix G2**, diagram A; supplementary data tables). TDS concentrations ranged from 67 to 9,160 mg/L, with a median of 1,080 mg/L.

Concentrations of some properties and constituents in water from alluvial aquifers in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most of these environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (89 percent of samples analyzed for the constituent), gross alpha radioactivity (38 percent), ammonia (14 percent), nitrate (7 percent), and nitrate plus nitrite (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (80 percent), manganese (67 percent), sulfate (67 percent), filtered iron (22 percent), pH (1 percent above upper limit), and chloride (1 percent).

Concentrations of some properties and constituents in water from alluvial aquifers exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in these environmental water samples that had concentrations greater than agricultural-use standards were sulfate (67 percent), manganese (67 percent), gross alpha radioactivity (38 percent), SAR (16 percent), TDS (9 percent), chloride (5 percent), boron (4 percent), and pH (1 percent above upper limit). Properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (38 percent), sulfate (4 percent), TDS (4 percent), and pH (1 percent above upper limit).

Terrace-deposit aquifers

The chemical composition of groundwater in terrace-deposit aquifers in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 89 wells, one agricultural drain, and three springs. Summary statistics calculated for available constituents are listed in Appendix E2. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram B). TDS concentrations were variable and indicated that most waters were fresh (58 percent of samples) and the remaining waters were slightly to moderately saline (**Appendix E2, Appendix G2;** diagram B; supplementary data tables). TDS concentrations ranged from 265 to 6,360 mg/L, with a median of 879 mg/L.

Concentrations of some properties and constituents in water from terrace-deposit aquifers in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most of these environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), nitrate (9 percent), nitrate plus nitrite (9 percent), gross alpha radioactivity (8 percent), ammonia (3 percent), and fluoride (2 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (84 percent), sulfate (61 percent), fluoride (14 percent), and manganese (10 percent).

Concentrations of some properties and constituents in water from terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in these environmental water samples that had concentrations greater than agricultural-use standards were sulfate (70 percent), TDS (16 percent), gross alpha radioactivity (8 percent), SAR (5 percent), and chloride (3 percent). Properties and constituents that had concentrations greater than livestock-use standards were gross

alpha radioactivity (8 percent), sulfate (2 percent), and TDS (2 percent).

7.2.2 White River aquifer and Wagon Bed confining unit

The White River aquifer and Wagon Bed confining unit are composed of the White River and Wagon Bed Formations, respectively. In the BHB, the White River Formation is present only as erosional remnants in the Bighorn Mountains, and the Wagon Bed Formation is present only in the Owl Creek Mountains **(Plate I)**. The White River Formation is classified as an aquifer and the Wagon Bed Formation as a confining unit in the BHB on the basis of hydrogeologic characteristics in the WRB. No water use for these hydrogeologic units has been reported in the BHB. Consequently, the physical and groundwater-quality characteristics of these hydrogeologic units were described previously in the WRB section of this report.

7.2.3 Lower Tertiary/Upper Cretaceous aquifer system

Hydrogeologic units composing the lower Tertiary/Upper Cretaceous aquifer system are described in this section of the report. This large, areally extensive aquifer system coincides with the boundaries of the structural basin proper and is thousands of feet thick in the interior basin. Many domestic and stock wells in the BHB are completed in this aquifer system. Characteristics of individual hydrogeologic units composing the aquifer system and the relation among the units are described.

The lower Tertiary/Upper Cretaceous aquifer system comprises lithostratigraphic units ranging in age from Eocene to Upper Cretaceous **(Plate III)**. The lower Tertiary/Upper Cretaceous aquifer system comprises five hydrogeologic units – the Willwood aquifer, Fort Union aquifer, Lance aquifer, Meeteetse aquifer and confining unit, and Mesaverde aquifer **(Plate III)**. These hydrogeologic units are not separated from one another by any regional confining units. The lower Tertiary/Upper Cretaceous aquifer system is confined below by the thick Cody confining unit, which separates the system from the underlying lower and middle Mesozoic aquifers and confining units **(Plate III)**. The lower Tertiary-age Willwood and Fort Union Formations, which contain the Willwood and Fort Union aquifers, respectively, generally are flat lying to gently dipping and crop out within the basin interior **(Plate I)**, whereas the Upper Cretaceous-age Lance, Meeteetse, and Mesaverde Formations, which contain the Lance aquifer, Meeteetse aquifer and confining unit, and Mesaverde aquifer, respectively, dip basinward and crop out near basin margins.

Individual sandstone beds compose the aquifers in the lower Tertiary/Upper Cretaceous aquifer system. The sandstone beds composing the aquifers are interbedded and commonly separated by fine-grained rocks with low hydraulic conductivity (shale, mudstone, claystone, or siltstone). Consequently, water in the sandstone aquifers likely is under various degrees of confinement and hydraulic connection or isolation. Well yields from the hydrogeologic units are directly related to the number and combined thickness of sandstone lenses or beds ("aquifers" or "subaquifers") penetrated (Lowry et al., 1976; Libra et al., 1981). Small well yields and highly variable (and commonly poor) water quality limit most uses to domestic and stock purposes.

7.2.3.1 Willwood and Fort Union aquifers

The physical and chemical characteristics of the Willwood and Fort Union aquifers in the BHB are described in this section of the report. The aquifers are described together in this report because they are nearly indistinguishable in the BHB. Much of this description of the physical characteristics of the Willwood and Fort Union aquifers was modified from Bartos et al. (2005).

Physical characteristics

The Paleocene-age Fort Union Formation comprises the Fort Union aquifer, and the Eocene-age Willwood Formation comprises the Willwood aquifer in the BHB **(Plate III)**. The aquifers are the uppermost hydrogeologic units in the lower Tertiary/Upper Cretaceous aquifer system. The Fort Union Formation is underlain by the Lance Formation **(Plate III)**. Many wells are installed in the aquifers because the Willwood and Fort Union Formations are at or near land surface throughout much of the basin; however, most wells are for stock and domestic use because of relatively low yield and variable water quality that precludes some uses without treatment (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994).

The Fort Union and Willwood Formations have many similar characteristics, and it is very difficult to distinguish one formation from another, especially in the subsurface (Keefer et al., 1998). Both formations are areally extensive **(Plate I)** and are composed primarily of fine- to coarse-grained sandstone beds interbedded with shale and other fine-grained rocks, locally with some conglomerate and coal deposits. Individual sandstones are sheet or channel sandstones that vary widely in geometry and thickness in the BHB (see for example Neasham and Vondra, 1972; Bown, 1975). Many channel sandstones in the Willwood Formation are ribbon sandstones (also known as "shoestring" sandstones) of very narrow width and thickness (generally less than about 10 ft in thickness) (Kraus, 2001, and references therein). The Fort Union Formation is primarily exposed along the basin margins, whereas the Willwood Formation is exposed throughout the central part of the basin **(Plate I)**. The Fort Union Formation unconformably underlies the Willwood Formation around the margins of the BHB, although the two formations probably are conformable in the

structurally deepest parts of the basin (Keefer et al., 1998). In most locations in the BHB, the Willwood Formation is highly variegated, but the presence or absence of this characteristic is not a criterion for differentiating it from the Fort Union Formation, even though many earlier investigators used this characteristic to differentiate the two formations (Keefer et al., 1998, and references therein).

On the basis of measured surface sections, the proportion of sandstone to fine-grained rocks in the Fort Union Formation (and by inference, the Willwood Formation) varies greatly by location and sequence examined (Roberts, 1998, and references therein). Lowry et al. (1976) reported that the average proportion of sandstone in the Willwood and Fort Union Formations, on the basis of driller's logs, ranged from 3 to 88 percent with a weighted average of about 25 percent. The reported thicknesses of both formations vary depending on location and whether measured surface sections or subsurface data are used. Estimates of maximum thickness of the Fort Union Formation vary widely, and, using measured surface sections or subsurface methods, range from 1,000–1,500 ft along the east and south basin margins to nearly 7,500–11,500 ft in the structurally deepest parts of the basin along the west or northwest basin margins (Hewett, 1926; Stow, 1938; Rogers et al., 1948; Pierce, 1948; Moore, 1961; Horn, 1963; Hickey, 1980; Keefer et al., 1998; Taylor, 1998). Estimates of the maximum thickness of the Willwood Formation in selected locations range from about 800 ft to nearly 5,000 ft (Van Houten, 1944; Neasham and Vondra, 1972; Gingerich, 1983; Keefer et al., 1998). The formations generally increase in thickness from east to west, and maximum thickness occurs in the structurally deepest parts of the basin along the western margin.

Individual sandstone beds in the Fort Union and Willwood Formations compose the main aquifers; in many cases, these beds are relatively thin, lenticular, and discontinuous. Sandstone beds composing the aquifers are interbedded and commonly separated by fine-grained rocks with low hydraulic conductivity such as shale, mudstone, or siltstone. Consequently, water in the sandstone aquifers likely is under varying degrees of confinement and hydraulic isolation. Water-table conditions may exist in the shallowest sandstones, and semiconfined or confined conditions are likely in deeper sandstones. In general, fine-grained sedimentary rocks (for example, siltstone, shale) in both formations are not likely to yield sufficient quantities of water to be considered aquifers, even though they may be saturated; static water levels in wells completed in the fine-grained rocks may be the same as in adjacent beds of sandstone. Well yields from both aquifers are directly related to the number and thickness of sandstone lenses or beds ("aquifers") penetrated (Lowry et al., 1976; Libra et al., 1981). Median combined spring and well yields for both aquifers are less than 10 gal/min **(Plate IX)**. Although not highly permeable, both aquifers are important sources of water because of their wide areal extent at or near the land surface in the BHB and because enough water can usually be obtained for domestic or stock purposes (but quality varies widely). Hydrogeologic data describing the Willwood and Fort Union aquifers, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Similarly to the Quaternary unconsolidated-deposit aquifers, the areal extent of the Willwood and Fort Union aquifers coincides with much of the rural population and irrigated cropland in the BHB, making these aquifers susceptible to contamination from human activities at the land surface. In fact, evidence of groundwater contamination by human activities has been detected as elevated nitrate concentrations and as organic compounds such as volatile organic compounds and pesticides (Plafcan et al., 1993; Susong et al., 1993; Eddy-Miller, 1998a,b; Eddy-Miller and Norris, 2001; Eddy-Miller and Remley, 2005; Bartos et al., 2005, 2009). Some of these contaminants may be transported to the Willwood and Fort Union aquifers where overlain by Quaternary-age unconsolidated deposits. In a statewide assessment of pesticides in Wyoming groundwater, the largest percentage of pesticide detections and the largest number of different pesticides detected were in samples from wells in the BHB, some of which were completed in the Willwood and Fort Union aquifers (Bartos et al., 2009).

Chemical characteristics

The chemical composition of groundwater from the Willwood and Fort Union aquifers is described in this section of the report.

7.2.3.1.1 Willwood aquifer

The chemical composition of groundwater in the Willwood aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 92 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram C). TDS concentrations were variable and indicated that about one-half the waters were slightly saline (51 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram C; supplementary data tables). TDS concentrations ranged from 352 to 9,000 mg/L, with a median of 1,350 mg/L.

Concentrations of some properties and constituents in water from the Willwood aquifer in the BHB 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 (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), ammonia (33 percent), molybdenum (15 percent), gross alpha radioactivity (14 percent), selenium (12 percent), nitrate plus nitrite (11 percent), uranium (10 percent), antimony (8 percent), cadmium (6 percent), and fluoride (4 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (96 percent), sulfate (74 percent), manganese (26 percent), fluoride (33 percent), pH (16 percent above upper limit), aluminum (10 percent exceeded lower and upper limits), filtered iron (5 percent), and chloride (4 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in these environmental water samples measured at concentrations greater than agricultural-use standards were SAR (80 percent), sulfate (74 percent), chloride (26 percent), TDS (24 percent), selenium (18 percent), gross alpha radioactivity (14 percent), manganese (5 percent), and pH (1 percent above upper limit). Properties and constituents measured at concentrations greater than livestock-use standards were selenium (18 percent), pH (16 percent above upper limit), gross alpha radioactivity (14 percent), sulfate (2 percent), and TDS (2 percent).

7.2.3.1.2 Fort Union aquifer

The chemical composition of groundwater in the Fort Union aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 31 wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram D). TDS concentrations were variable and indicated that the water ranged from fresh to moderately saline (**Appendix E2; Appendix G2**, diagram D; supplementary data tables). TDS concentrations ranged from 372 to 4,920 mg/L, with a median of 1,550 mg/L.

The chemical composition of groundwater in the Fort Union aquifer also was characterized and the quality evaluated on the basis of one produced-water sample from a well. Summary statistics calculated for available constituents are listed in **Appendix F2**. The TDS concentration (1,610 mg/L) from the produced-water sample indicated that the water was slightly saline (Appendix F2; supplementary data tables).

Concentrations of some properties and constituents in water from the Fort Union aquifer in the BHB 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 a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (80 percent of samples analyzed for the constituent), ammonia (50 percent), gross alpha radioactivity (14 percent), and fluoride (3 percent). Concentrations of several properties and constituents exceeded aesthetic standards (SMCLs) for domestic use: TDS (97 percent), sulfate (78 percent), filtered iron (30 percent), manganese (30 percent), fluoride (28 percent), chloride (9 percent), and pH (6 percent above upper limit).

Chemical analyses were available for only a few properties and constituents from one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of TDS and sulfate that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (81 percent), SAR (65 percent), TDS (41 percent), mercury (20 percent), chloride (19 percent), gross alpha radioactivity (14 percent), manganese (10 percent), selenium (7 percent), and boron (5 percent). One constituent and one property had concentrations greater than livestock-use standards: gross alpha radioactivity (14 percent) and pH (6 percent above upper limit).

The produced-water sample had a concentration of one constituent that exceeded agricultural-use standards: sulfate. No properties or constituents in the produced-water sample exceeded livestock-use standards.

7.2.3.2 Lance aquifer

The physical and chemical characteristics of the Lance aquifer in the BHB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Lance Formation comprises the Lance aquifer in the BHB **(Plate III)**. The aquifer is part of the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Lance aquifer consists of sandstone interbedded with shale, claystone, siltstone, and thin coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the aquifer in the BHB ranges from 800 ft in the southwest to 1,800 ft in the north (Lowry et al., 1976; Libra et al., 1981, Table IV-1). The Lance Formation is overlain by the Fort Union Formation and underlain by the Meeteetse Formation **(Plate III)**. Confined conditions predominate in the Lance aquifer, but unconfined (water-table) conditions are likely in outcrop areas of the Lance Formation. Sandstone beds within the aquifer have been developed for stock, domestic, and limited

public-supply use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. Many of the lenticular, laterally discontinuous sandstones are confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Lance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Lance aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from eight wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (88 percent of samples) and the remaining waters were slightly saline (Appendix E2; supplementary data tables). TDS concentrations ranged from 591 to 1,260 mg/L, with a median of 902 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations from produced-water samples were variable and ranged from slightly to moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,210 to 4,880 mg/L, with a median of 1,760 mg/L.

Concentrations of some properties and constituents in water from the Lance aquifer in the BHB 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 (USEPA MCLs and HALs): fluoride (29 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), fluoride (57 percent), pH (50 percent above upper limit), and sulfate (38 percent).

For the water-quality analyses from produced-water samples, chemical analyses of many properties and constituent analyses were not available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), pH (50 percent above upper limit), chloride (33 percent), and sulfate (33 percent).

Concentrations of some properties and constituents in water from the Lance aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (60 percent), sulfate (50 percent), and chloride (12 percent). The property that had values greater than livestock-use standards was pH (50 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (100 percent), chloride (67 percent), and TDS (33 percent). The produced-water samples generally had values of one property that exceeded livestock-use standards: pH (50 percent above upper limit).

7.2.3.3 Meeteetse aquifer and confining unit

The physical and chemical characteristics of the Meeteetse aquifer and confining unit in the BHB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Meeteetse Formation, and, in places, tongues of the Upper Cretaceous-age Lewis Shale, compose the Meeteetse aquifer and confining unit in the BHB **(Plate III)**. The aquifer is part of the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Meeteetse confining unit and aquifer consists of lenticular, clayey to silty, fine-grained, poorly indurated sandstone interbedded with shale, claystone, siltstone, bentonite, and sparse thin coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Where present, the Lewis Shale is interbedded with the Meeteetse Formation and acts as a confining unit **(Plate III)**. Consequently, the hydrogeologic unit is considered both a confining unit and aquifer herein. The reported thickness of the hydrogeologic unit in the BHB ranges from 650 ft in the southeast to 1,200 ft in the northwest (Lowry et al., 1976; Libra et al., 1981, table IV-1). The Meeteetse Formation is overlain by the Lance Formation and underlain by the Mesaverde Formation **(Plate III)**. Confined conditions predominate, but unconfined (water-table) conditions are likely in outcrop areas. Sandstone beds within the aquifer have potential for development for stock and domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. The lenticular, laterally discontinuous sandstones are often confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Meeteetse confining unit and aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Meeteetse confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (60 percent of samples) and the remaining waters were fresh (**Appendix E2; supplementary data tables**). TDS concentrations ranged from 936 to 1,400 mg/L, with a median of 1,200 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples indicated that most waters were slightly saline (67 percent of samples) and the remaining water was moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,150 to 5,520 mg/L, with a median of 2,300 mg/L.

Concentrations of some properties and constituents in the Meeteetse confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (60 percent), filtered iron (33 percent), manganese (33 percent), and pH (20 percent above upper limit).

For the three produced-water samples, chemical analyses for many properties and constituents were not available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards are limited. One produced-water sample had concentrations of one constituent that exceeded health-based standards (USEPA MCLs): fluoride. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: chloride (100 percent), TDS (100 percent), filtered iron (100 percent), fluoride (50 percent), and pH (33 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. One constituent and one property in environmental water samples had concentrations greater than agricultural-use standards: sulfate (100 percent) and SAR (20 percent). One property (pH) had values greater than livestock-use standards (20 percent above upper limit).

The three produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), chloride (100 percent), and TDS (100 percent). Some produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (33 percent above upper limit) and TDS (33 percent).

7.2.3.4 Mesaverde aquifer

The physical and chemical characteristics of the Mesaverde aquifer in the BHB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Mesaverde Formation comprises the Mesaverde aquifer in the BHB **(Plate III)**. The aquifer is the lowermost hydrogeologic unit in the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Mesaverde aquifer consists of a variable sequence of massive, lenticular, fine- to coarse-grained sandstone, carbonaceous shale, and lesser amounts of coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The sandstones commonly are lenticular and laterally discontinuous, and range in thickness from 5 to 40 ft (Plafcan et al., 1993). The lowermost part of the formation, known as the "Eagle Sandstone," consists primarily of fine-grained sandstone and shaley sandstone. The reported thickness of the Mesaverde Formation ranges from 900 ft in the eastern BHB to 1,800 ft in the south-central BHB (Libra et al., 1981, Table IV-1). The Mesaverde aquifer generally is confined above by the Meeteetse aquifer and confining unit and is confined below by the Cody confining unit **(Plate III)**. Confined conditions predominate, and unconfined (water-table) conditions are likely in outcrop areas of the Mesaverde Formation. Sandstone beds within the aquifer have potential for development for stock, domestic, or limited public-supply use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. The lenticular, laterally discontinuous sandstones commonly are confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Mesaverde aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Mesaverde aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 24 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-

ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram E). TDS concentrations were variable and indicated that most waters were slightly saline (73 percent of samples) and the remaining waters were fresh to moderately saline (**Appendix E2; Appendix G2**, diagram E; supplementary data tables). TDS concentrations ranged from 395 to 5,510 mg/L, with a median of 1,770 mg/L.

The chemical composition of groundwater in the Mesaverde aquifer also was characterized and the quality evaluated on the basis of 21 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram A). TDS concentrations from produced-water samples were variable and ranged from fresh to moderately saline, and most waters were slightly saline (76 percent) (**Appendix F2; Appendix H2,** diagram A; supplementary data tables). TDS concentrations ranged from 965 to 7,400 mg/L, with a median of 2,390 mg/L.

Concentrations of some properties and constituents in water from the Mesaverde aquifer in the BHB 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 (USEPA MCLs and HALs): gross alpha radioactivity (100 percent of samples analyzed for the constituent) and boron (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (96 percent), sulfate (81 percent), manganese (43 percent), filtered iron (29 percent), fluoride (8 percent), and chloride (4 percent).

Some water-quality analyses were available from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): boron (100 percent) and fluoride (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), chloride (60 percent), fluoride (50 percent), manganese (50 percent), sulfate (20 percent), and pH (14 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent), sulfate (85 percent), mercury (60 percent), TDS (38 percent), SAR (29 percent), chloride (12 percent), and boron (11 percent). Properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (100 percent), TDS (4 percent), and sulfate (4 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), boron (100 percent), chloride (80 percent), TDS (76 percent), and sulfate (27 percent). The produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (14 percent above upper limit) and TDS (5 percent).

7.2.3.4.1 Eagle Sandstone

The chemical composition of groundwater in the Eagle Sandstone in the BHB was characterized and the quality evaluated on the basis of one produced-water sample from a well. The TDS concentration (3,680 mg/L) indicated that the water was moderately saline.

Concentrations of some characteristics and constituents in the Eagle Sandstone in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. The produced-water sample had concentrations of one characteristic (TDS) and one constituent (sulfate) that exceeded aesthetic standards for domestic use.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the BHB. The produced-water sample had concentrations of two constituents that exceeded agricultural-use standards: chloride and sulfate. The produced-water sample had no concentrations of characteristics or constituents that exceeded livestock-use standards.

7.2.3.5 Recharge, discharge, and groundwater movement

Recharge to the Willwood and Fort Union aquifers likely is primarily from areal infiltration and percolation of precipitation in outcrop areas, and from localized recharge beneath ephemeral drainages during periods of runoff. Recharge also is likely in areas where the Willwood and Fort Union Formations are overlain by saturated Quaternary unconsolidated deposits (alluvium and terrace deposits) (Swenson, 1957; Berry and Littleton, 1961; Lowry et al., 1976).

Recharge to aquifers in Upper Cretaceous-age lithostratigraphic units likely is primarily from infiltration and percolation of

precipitation in outcrop areas, and from localized recharge beneath ephemeral drainages during periods of runoff (Swenson, 1957; Berry and Littleton, 1961). Recharge in outcrop areas likely is largest where sandstone beds dipping toward the basin interior are exposed along basin margins (Berry and Littleton, 1961). The sandstone beds (aquifers) commonly are confined by interbedded shales with much lower permeability, resulting in development of confined conditions as water moves downgradient. In places, fractures may provide hydraulic connection between confined sandstone aquifers and allow for movement of water between them (Berry and Littleton, 1961). Berry and Littleton also noted that hydraulic connection between confined sandstone aquifers due to pressure head differential alone was possible even when fractures were not present, depending on confining unit permeability, thickness, and areal extent.

Discharge from the lower Tertiary/Upper Cretaceous aquifer system is both natural and anthropogenic. Groundwater discharges through seeps, springs, interformational movement, and gaining streams (Lowry et al., 1976; Libra et al., 1981). Lowry et al. (1976, Sheet 1) also noted that perennial streamflow gains and losses associated with discharge from and recharge to the Willwood and Fort Union aquifers in the center of the basin "is not great enough to be discernible from other minor factors affecting streamflow, such as evapotranspiration." The primary anthropogenic sources of discharge from the lower Tertiary/Upper Cretaceous aquifer system are domestic, stock, and oil and gas wells.

Potentiometric-surface maps of aquifers in the lower Tertiary/Upper Cretaceous aquifer system in the BHB have not been constructed, and regional groundwater flow has not been described. The discontinuous and lenticular characteristic of the sandstones composing the aquifers makes it difficult to create and interpret such maps (Libra et al., 1981). In addition, the sandstones are interbedded with fine-grained rocks, and the amount of hydraulic connection between individual sandstone aquifers is difficult to assess. However, the authors suspect that groundwater flow in the shallow aquifers is primarily local and related to topography, with discharge occurring in some areas along streams adjacent to local recharge areas. The amount of regional groundwater flow and the relation between local and possible intermediate and regional groundwater flow are unknown.

7.2.4 Cody confining unit

The physical and chemical characteristics of the Cody confining unit in the BHB are described in this section of the report.

Physical characteristics

The regionally extensive Cody confining unit is composed of the Upper Cretaceous-age Cody Shale. This thick unit confines and separates the underlying lower and middle Mesozoic aquifers and confining units from the overlying lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The reported thickness of the Cody confining unit ranges from about 2,100 ft in the northwest to 3,000 ft in the southeastern Bighorn Basin (Lowry et al., 1976; Libra et al., 1981). The upper part of the Cody Shale is composed of gray sandy shale interbedded with shaley sandstone, and the lower part is composed predominantly of dark gray marine shale with some glauconitic sandstone and thin beds of bentonite (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Sandstones and fractured zones in the Cody confining unit yield small quantities of water to wells at some locations in the BHB, although poor water quality limits most uses (Libra et al., 1981; Western Water Consultants Inc., 1982a,b, 1983b, 1986; Plafcan et al., 1993; Susong et al., 1993). Little hydrogeologic information is available describing the Cody confining unit, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Cody confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram F). TDS concentrations were variable and indicated that one-half of the waters were slightly saline (50 percent of samples) and the remaining waters were fresh or moderately saline **(Appendix E2; Appendix G2**, diagram F; supplementary data tables). TDS concentrations ranged from 660 to 8,290 mg/L, with a median of 2,350 mg/L.

The chemical composition of groundwater in the Cody confining unit also was characterized and the quality evaluated on the basis of five produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from fresh to moderately saline, and most of the waters were slightly saline (60 percent) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,440 to 6,750 mg/L, with a median of 2,940 mg/L.

Concentrations of some properties and constituents in water from the Cody confining unit in the BHB 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 (USEPA MCLs and HALs): boron (29 percent of samples analyzed for the constituent) and nitrate plus nitrite (14 percent). Concentrations of several properties and constituents

exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (80 percent), manganese (33 percent), chloride (20 percent), fluoride (20 percent), and pH (11 percent above upper limit).
Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), pH (60 percent above upper limit), sulfate (60 percent), and chloride (40 percent).

Concentrations of some properties and constituents in water from the Cody confining unit exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (90 percent), SAR (70 percent), boron (57 percent), TDS (50 percent), copper (50 percent), mercury (50 percent), manganese (33 percent), chloride (30 percent), selenium (17 percent), and pH (11 percent above upper limit). Properties and constituents that had concentrations greater than livestock-use standards were TDS (20 percent), sulfate (20 percent), and pH (11 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (100 percent), chloride (40 percent), and sulfate (60 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: pH (60 percent above upper limit), TDS (20 percent), and chloride (20 percent).

7.2.5 Lower and middle Mesozoic aquifers and confining units

The lower and middle Mesozoic aquifers and confining units is a stratigraphic and hydrogeologic sequence that "consists of impermeable shales that isolate discrete water-bearing sandstone and carbonate units" (Libra et al., 1981, p. 58). Rocks composing the lower and middle Mesozoic aquifers and confining units range in age from Lower Triassic to Upper Cretaceous **(Plate III)**. Although classified as confining units, shales within the sequence "may have enhanced permeabilities in fractured zones, along bedding planes, and within coarser clastic beds" (Libra et al., 1981, p. 58, and references therein). The complex intertonguing and interfingering between the various facies within the sequence creates numerous small permeable zones that function as individual aquifers (or subaquifers). In addition, many of the lithostratigraphic units within this sequence consist of more than one facies, some of which function as confining units (shales and siltstones) and some of which function as aquifers (sandstones and carbonate). Consequently, several of the hydrogeologic units have been defined herein as both aquifer and confining unit **(Plate III)**. Excluding the numerous oil wells completed in the lower and middle Mesozoic aquifers and confining units, the relatively few wells completed in the hydrogeologic sequence are located primarily in outcrop areas around the basin margin where drilling depth is relatively shallow and waters are relatively fresh. Most of these wells are completed for domestic or stock purposes. Most geologic and hydrogeologic data for the lower and middle Mesozoic aquifers and confining units were generated during petroleum exploration. Groundwater in many of the hydrogeologic units is highly mineralized and unsuitable for most uses.

7.2.5.1 Frontier aquifer

The physical and chemical characteristics of the Frontier aquifer in the BHB are described in this section of the report.

Physical characteristics

The Upper Cretaceous-age Frontier Formation comprises the Frontier aquifer in the BHB. The Frontier aquifer consists of lenticular, fine- to medium-grained, argillaceous sandstone, and lenticular conglomeratic sandstone beds, interbedded with shale and lesser amounts of lignite and bentonite (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the aquifer in the BHB ranges from 450 ft in the west to 700 ft in the southeast (Libra et al., 1981, table IV-1). Lowry et al. (1976, Sheet 1) reported that the Frontier Formation contains less than 50 percent sandstone in the basin. The Frontier aquifer is confined above by the thick, regional Cody confining unit and below by the Mowry–Thermopolis confining unit **(Plate III)**. Confined conditions predominate, but unconfined (water-table) conditions have been reported in outcrop areas in the northeastern BHB (Western Water Consultants, Inc., 1982a,b). Permeability is primarily intergranular and dependent on clay content, swelling and floculating properties of the clay minerals, and fluid salinity (Baptist et al., 1952). Recharge to the Frontier aquifer likely is by direct infiltration of precipitation on outcrop areas.

Sandstone beds within the aquifer are considered to have some potential for development, although yields are likely to be small and adequate only for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Western Water Consultants, Inc. (1982a,b) evaluated the Frontier Formation as a potential source of public supply in the northeastern BHB. They defined the lenticular interbedded sandstones in the Frontier Formation as subaquifers, but noted

that development potential as a source of public supply was poor because of the low permeability, variable thickness, and the discontinuous nature of sandstone beds.

Chemical characteristics

The chemical composition of groundwater in the Frontier aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from nine wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram G). TDS concentrations were variable and indicated that most waters were slightly saline (58 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram G; supplementary data tables). TDS concentrations ranged from 758 to 5,210 mg/L, with a median of 1,530 mg/L.

The chemical composition of groundwater in the Frontier aquifer also was characterized and the quality evaluated on the basis of 133 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram G). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny, and indicated that most of the water was moderately saline (60 percent) (**Appendix F2; Appendix H2**, diagram B; supplementary data tables). TDS concentrations ranged from 1,470 to 81,800 mg/L, with a median of 6,630 mg/L.

Concentrations of some properties and constituents in water from the Frontier aquifer in the BHB 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 (USEPA MCLs and HALs): boron (10 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (83 percent), pH (50 percent above upper limit), filtered iron (20 percent), manganese (20 percent), and fluoride (17 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): boron (100 percent) and fluoride (17 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples), filtered iron (100 percent), chloride (79 percent), fluoride (67 percent), sulfate (46 percent), and pH (19 percent above upper limit). TDS concentrations in 20 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Frontier aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (92 percent), SAR (67 percent), boron (60 percent), mercury (50 percent), pH (25 percent above upper limit), and TDS (25 percent). Properties and constituents measured at concentrations greater than livestock-use standards were pH (50 percent above upper limit), sulfate (8 percent), and TDS (8 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), boron (100 percent), chloride (95 percent), TDS (92 percent), sulfate (47 percent), filtered iron (23 percent), and pH (1 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (65 percent), chloride (52 percent), boron (20 percent), pH (19 percent above upper limit), and sulfate (4 percent).

7.2.5.2 Mowry–Thermopolis confining unit

The physical and chemical characteristics of the Mowry–Thermopolis confining unit in the BHB are described in this section of the report.

Physical characteristics

The Mowry–Thermopolis confining unit is composed primarily of the the Upper Cretaceous-age Mowry Shale and the Lower Cretaceous-age Thermopolis Shale, but also contains the Lower Cretaceous-age Muddy Sandstone **(Plate III)**. The Mowry Shale is a confining unit that consists of thin-bedded, resistant/brittle shale, with thin sandstone and bentonite beds in the upper part (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Muddy Sandstone comprises the Muddy Sandstone aquifer, which is confined above by the Thermopolis Shale and below by the Mowry Shale **(Plate III)**. The Muddy Sandstone (formerly considered a member of the Thermopolis Shale) is composed of massive sandstone interbedded with mudstone, siltstone, shale, bentonite, and some conglomerate (Paull, 1962; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Thermopolis Shale is a confining unit that consists of soft black shale with sandy, silty, and bentonitic zones

(Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the Mowry–Thermopolis confining unit, including the Muddy Sandstone aquifer, is greater than 700 ft in the BHB (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the Muddy Sandstone aquifer ranges from 10 to 50 ft (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b; Plafcan et al., 1993). The Mowry–Thermopolis confining unit confines and separates the underlying Cloverly aquifer from the overlying Frontier aquifer **(Plate III)**.

With the exception of oil wells, relatively few wells are installed in the Mowry–Thermopolis confining unit; development is limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Although the Mowry and Thermopolis Shales are confining units, both yield small quantities of water to wells and springs at some locations in the BHB, especially from brittle, fractured shales or sandy zones (Lowry et al., 1976; Libra et al., 1981). The poor water quality determined during this study would preclude most uses without treatment. Most information describing the formations is from oil-field data. Hydrogeologic information available describing the Mowry–Thermopolis confining unit, including well-yield and spring-discharge measurements and other hydraulic properties for all three lithostratigraphic units composing it, are summarized on **Plate IX**.

Chemical characteristics

Chemical characteristics of the Mowry confining unit, Muddy Sandstone aquifer, and Thermopolis confining unit are presented and described in this section of the report.

7.2.5.2.1 Mowry confining unit

The chemical composition of groundwater in the Mowry confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from four wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were highly variable and indicated that waters ranged from fresh to very saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 362 to 19,200 mg/L, with a median of 1,150 mg/L.

The chemical composition of groundwater in the Mowry confining unit also was characterized and the quality evaluated on the basis of five produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,080 to 7,950 mg/L, with a median of 1,820 mg/L.

Concentrations of some properties and constituents in water from the Mowry confining unit in the BHB 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 (USEPA MCLs and HALs): fluoride (29 percent of samples analyzed for the constituent) and boron (20 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (86 percent), sulfate (71 percent), filtered iron (33 percent), manganese (33 percent), and fluoride (29 percent). TDS concentrations in 14 percent of environmental water samples exceeded State of Wyoming Class IV standards.

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples), chloride (40 percent), and pH (20 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (86 percent), SAR (43 percent), TDS (43 percent), boron (20 percent), and chloride (14 percent). One constituent and one property had concentrations greater than livestock-use standards: sulfate (14 percent) and TDS (14 percent).

The produced-water samples generally had concentrations of one constituent and one property that exceeded agricultural-use standards: chloride (40 percent) and TDS (40 percent). Some produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (20 percent above upper limit) and TDS (20 percent).

7.2.5.2.2 Muddy Sandstone aquifer

The chemical composition of groundwater in the Muddy Sandstone aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were fresh (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 688 to 1,570 mg/L, with a median of 1,100 mg/L.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the BHB also was characterized and the quality evaluated on the basis of 23 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram C). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny, and indicated that most of the water was slightly saline (48 percent) (Appendix F2; Appendix H2, diagram C; supplementary data tables). TDS concentrations ranged from 1,040 to 47,300 mg/L, with a median of 4,810 mg/L.

Concentrations of some properties and constituents in water from the Muddy Sandstone aquifer in the BHB 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 (USEPA MCLs and SMCLs): fluoride (20 percent of the samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), pH (80 percent above upper limit), sulfate (60 percent), and fluoride (40 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), sulfate (59 percent), chloride (57 percent), and pH (5 percent below lower limit and 10 percent above upper limit). TDS concentrations in 9 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were SAR (80 percent), sulfate (60 percent), boron (25 percent), chloride (20 percent), and pH (20 percent above upper limit). One property had values greater than livestock-use standards: pH (80 percent above upper limit).

The produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: filtered iron (100 percent), TDS (78 percent), chloride (74 percent), sulfate (64 percent), and pH (5 percent below lower limit). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (48 percent), chloride (22 percent), sulfate (14 percent), and pH (5 percent below lower limit and 10 percent above upper limit).

7.2.5.2.3 Thermopolis confining unit

The chemical composition of groundwater in the Thermopolis confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (60 percent of samples) and the remaining waters were slightly or very saline (supplementary data tables). TDS concentrations ranged from 218 to 25,100 mg/L, with a median of 638 mg/L.

Concentrations of some properties and constituents in water from the Thermopolis confining unit in the BHB 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 frequently exceeded health-based standards (USEPA MCLs and HALs): cadmium (100 percent of samples analyzed for the constituent) and selenium (50 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (80 percent), manganese (67 percent), sulfate (40 percent), filtered iron (33 percent), pH (25 percent below lower limit), and fluoride (20 percent). TDS concentrations in 20 percent of environmental water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in the environmental water samples that had concentrations greater than agricultural-use standards were cadmium (100 percent), cobalt (100 percent), sulfate (80 percent), manganese (67 percent), selenium (50 percent), SAR (40 percent), pH (25 percent below lower limit), chloride (20 percent), and TDS (20 percent). Several properties and constituents were measured at concentrations greater than livestock-use standards: cadmium (100 percent), selenium (50 percent), pH (25 percent below lower limit), sulfate (20 percent), and TDS (20 percent).

7.2.5.3 Cloverly aquifer

The physical and chemical characteristics of the Cloverly aquifer in the BHB are described in this section of the report.

Physical characteristics

The Lower Cretaceous-age Cloverly Formation comprises the Cloverly aquifer **(Plate III)**. The Cloverly Formation consists of three distinctive units in the BHB – an upper sandstone interbedded with silty sandstone and shale, known as the "Dakota Sandstone"; a middle shale unit with sparse sandstone lenses; and a lower lenticular sandstone with conglomeratic sandstone and some siltstone and shale, known as the "Lakota Sandstone" (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b, 1986; Plafcan et al., 1993). The reported thickness of the Cloverly Formation, including all three lithologic units, ranges from about 85 ft in the southeastern part of the Bighorn Basin to about 470 ft in the northwestern part (Libra et al., 1981, Table IV-1). The aquifer is confined above by the Mowry–Thermopolis confining unit and below by the Morrison confining unit **(Plate III)**. Hydrogeologic information describing the Cloverly aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate IX**.

The Cloverly aquifer was examined as a potential source of public supply in the northeastern BHB (Western Water Consultants, Inc., 1982a,b). Western Water Consultants reported that both sandstone units were permeable and ranged in thickness from 70 to 90 ft. The investigators speculated that the middle shale unit may function as a leaky confining unit between the two sandstone units. The sandstone units were reported to be confined where buried but unconfined in outcrop areas. Permeability was reported to be intergranular and to be fracture enhanced in anticlines.

Chemical characteristics

The chemical composition of groundwater in the Cloverly aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2,** diagram H). TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram H; supplementary data tables). TDS concentrations ranged from 814 to 3,080 mg/L, with a median of 2,350 mg/L.

The chemical composition of groundwater in the Cloverly aquifer in the BHB also was characterized and the quality evaluated on the basis of 27 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram D).TDS concentrations from produced waters were variable and indicated that most waters were moderately saline (56 percent of samples) and the remaining waters were slightly or very saline **(Appendix F2; Appendix H2**, diagram D; supplementary data tables). TDS concentrations ranged from 1,320 to 11,500 mg/L, with a median of 4,290 mg/L.
Concentrations of some properties and constituents in water from the Cloverly aquifer in the BHB 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 (USEPA MCLs and HALs): boron (29 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), filtered iron (50 percent), manganese (50 percent), boron (29 percent), pH (17 percent above upper limit), and fluoride (10 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (70 percent), sulfate (64 percent), and pH (4 percent below lower limit and 8 percent above upper limit). TDS concentrations in 7 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent), SAR (60 percent), TDS (60 percent), and mercury (50 percent). Values of one property (pH) exceeded livestock-use standards (17 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (93 percent), TDS (93 percent), and sulfate (64 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (33 percent), pH (4 percent below lower limit and 8 percent above upper limit), chloride (7 percent), and sulfate (4 percent).

7.2.5.4 Morrison confining unit and aquifer

The physical and chemical characteristics of the Morrison confining unit and aquifer in the BHB are described in this section of the report.

Physical characteristics

The Upper Jurassic-age Morrison Formation comprises the Morrison confining unit and aquifer in the BHB. The Morrison confining unit and aquifer consists primarily of interbedded variegated shale and mudstone, with lesser silty fine-grained sandstone, limestone, and lenses of conglomerate (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The fine-grained lithologies (for example, shale and mudstone) are considered confining units, whereas the interbedded sandstone beds are considered local aquifers or subaquifers (Libra et al., 1981; Plafcan et al., 1993). The Morrison Formation is defined herein as a confining unit and aquifer **(Plate III)**. The reported thickness of the Morrison confining unit and aquifer in the BHB ranges from 75 ft in the northwest to 300 ft in the southeast (Libra et al., 1981, table IV-1). The Morrison Formation is overlain by the Cloverly Formation and underlain by the Sundance Formation **(Plate III)**. Confined conditions likely predominate in the Morrison confining unit and aquifer except in outcrop areas. Sandstone beds within the Morrison confining unit and aquifer are considered to have limited potential for development because of small outcrop area and small yields adequate only for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Little hydrogeologic information is available describing the Morrison confining unit, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Morrison confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations (604 and 4,780 mg/L) indicated that waters were fresh and moderately saline (Appendix E2; supplementary data tables).

The chemical composition of groundwater in the Morrison confining unit and aquifer in the BHB also was characterized and the quality evaluated on the basis of 10 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,270 to 18,700 mg/L, with a median of 7,130 mg/L.

Concentrations of some properties and constituents in the Morrison confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property) and sulfate (50 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed for in produced-water samples had available health-based standards (USEPA MCLs and HALs) for comparison. The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (70 percent), sulfate (50 percent), and pH (20 percent above upper limit). TDS concentrations in 40 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (50 percent), SAR (50 percent), and TDS (50 percent). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

The produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (100 percent), chloride (80 percent), and sulfate (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: chloride (60 percent), TDS (60 percent), and pH (20 percent above upper limit).

7.2.5.5 Sundance confining unit and aquifer

The physical and chemical characteristics of the Sundance confining unit and aquifer are described in this section of the report.

Physical characteristics

The Middle and Upper Jurassic-age Sundance Formation comprises the Sundance confining unit and aquifer in the BHB **(Plate III)**. The Sundance aquifer consists primarily of greenish-gray shale interbedded with glauconitic sandstone, siltstone, and limestone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Low permeability fine-grained lithologies (for example, shale, siltstone) are considered confining units, whereas the interbedded sandstone beds are considered local aquifers or subaquifers (Libra et al., 1981; Plafcan et al., 1993). The Sundance Formation is defined

herein as a confining unit and aquifer **(Plate III)**. The reported thickness of the hydrogeologic unit in the BHB ranges from 200 to 370 ft (Lowry et al., 1976; Libra et al., 1981, Table IV-1; Western Water Consultants, Inc., 1982a,b, 1986). The Sundance Formation is overlain by the Morrison Formation and underlain by the Gypsum Spring Formation **(Plate III)**. Confined conditions likely predominate except in outcrop areas, where unconfined (water-table) conditions are likely. Sandstone beds within the aquifer are considered to have limited potential for development because of small extent and small yields only adequate for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1986; Plafcan et al., 1993). Little hydrogeologic information is available describing the Sundance confining unit and aquifer, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Sundance confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2.** The TDS concentration (708 mg/L) indicated that the water was fresh (Appendix E2; supplementary data tables).

The chemical composition of groundwater in the Sundance confining unit and aquifer in the BHB also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations from produced waters were variable and ranged from slightly to very saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,280 to 14,300 mg/L, with a median of 3,080 mg/L.

Concentrations of some properties and constituents in the Sundance confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations in one environmental water sample with health-based standards (USEPA MCLs and HALs), the environmental water was suitable for domestic use. One property (TDS) and one constituent (sulfate) exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Most water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed in produced-water samples had available health-based standards (USEPA MCLs and HALs) for comparison. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: chloride (100 percent of samples analyzed for the constituent), TDS (100 percent), sulfate (67 percent), and pH (11 percent above upper limit). TDS concentrations in 22 percent of produced-water samples from the Sundance aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agriculture and livestock use in the BHB. Sulfate was measured in the environmental water sample at a concentration greater than the agricultural-use standard. No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (100 percent), TDS (100 percent), and sulfate (67 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: sulfate (22 percent), TDS (22 percent), and pH (11 percent above upper limit).

7.2.5.6 Gypsum Spring confining unit and aquifer

The physical and chemical characteristics of the Gypsum Spring confining unit and aquifer in the BHB are described in this section of the report.

Physical characteristics

The Middle Jurassic-age Gypsum Spring Formation comprises the Gypsum Spring confining unit and aquifer in the BHB. The Gypsum Spring confining unit and aquifer consists primarily of reddish-brown siltstone, claystone, and shale, with thin limestone and massive gypsum beds (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Low-permeability fine-grained lithologies (for example, shale, siltstone) are considered confining units, whereas solution zones in gypsum beds are considered local aquifers or subaquifers, although with very poor groundwater quality (Libra et al., 1981; Plafcan et al., 1993). The Gypsum Spring Formation is defined as a confining unit and aquifer **(Plate III)**. The reported thickness of the Gypsum Spring Formation in the BHB ranges from 200 to 370 ft (Lowry et al., 1976; Libra et al., 1981, table IV-1; Western Water Consultants, Inc., 1982a,b, 1986). The Gypsum Spring Formation is overlain by the Sundance Formation and is underlain by the Nugget Sandstone or Chugwater Group, depending on the presence or absence of the Nugget Sandstone **(Plate III)**. Confined conditions likely predominate in the Gypsum Spring confining unit and aquifer except in outcrop areas, where unconfined (water-table) conditions are likely.

Very few wells are completed in the Gypsum Spring confining unit and aquifer, and potential for development for any use is very limited because of small outcrop extent, probable poor water quality, and availability of better groundwater sources (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1986; Plafcan et al., 1993). Very little hydrogeologic information is available describing the Gypsum Spring confining unit and aquifer, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Gypsum Spring confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples analyzed for the property) and the remaining waters were fresh (Appendix E2; supplementary data tables). TDS concentrations ranged from 342 to 2,650 mg/L, with a median of 1,830 mg/L.

Concentrations of some properties and constituents in water from the Gypsum Spring confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (75 percent) and TDS (75 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. One constituent and one property in environmental water samples had concentrations greater than agricultural-use standards: sulfate (75 percent) and TDS (50 percent). No properties or constituents exceeded State of Wyoming livestock standards.

7.2.5.7 Nugget aquifer

No information was located to describe the physical and chemical characteristics of the Nugget aquifer in the BHB; however, this aquifer is described in the WRB section of this report.

7.2.5.8 Recharge, discharge, and groundwater movement

Recharge to lower and middle Mesozoic aquifers and confining units in the BHB is primarily by infiltration of precipitation and streamflow in outcrop areas (Berry and Littleton, 1961; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b). Infiltration of water from overlying saturated Quaternary unconsolidated deposits and interformational flow in fracture zones along anticlines also may contribute to recharge locally (Berry and Littleton, 1961; Lowry et al., 1976; Plafcan et al., 1993).

Discharge from lower and middle Mesozoic aquifers and confining units is both natural and anthropogenic. Groundwater discharges from lower and middle Mesozoic aquifers and confining units through seeps, springs, interformational movement, and gaining streams (Lowry et al., 1976; Libra et al., 1981). The primary anthropogenic sources of discharge from aquifers in the lower and middle Mesozoic aquifers and confining units likely are oilfield wells.

Potentiometric-surface maps have not been constructed for any of the lower and middle Mesozoic aquifers and confining units. Groundwater movement in these hydrogeologic units is assumed to be from outcrop areas (assumed to represent recharge areas) to the basin interior (Berry and Littleton, 1961; Lowry et al., 1976; Libra et al., 1981).

7.2.6 Chugwater–Dinwoody aquifer and confining unit

The physical and chemical characteristics of the Chugwater–Dinwoody aquifer and confining unit in the BHB are described in this section of the report.

Physical characteristics

The Chugwater aquifer is composed of the Lower and Upper Triassic-age Chugwater Group or Formation. The Dinwoody confining unit is composed of the Lower Triassic-age Dinwoody Formation. The Chugwater–Dinwoody aquifer and confining unit confines and separates the underlying Paleozoic aquifer system from the overlying lower and middle Mesozoic aquifers and confining units **(Plate III)**. The reported thickness of the Chugwater–Dinwoody aquifer and confining unit ranges from about 450 to 1,200 ft (Libra et al., 1981, table IV-1; Western Water Consultants, Inc., 1983b; Jarvis, 1986a). The Chugwater Group or Formation is composed of distinctive red beds and includes fine-grained sandstone, siltstone, and shale with some thin lenticular beds of limestone and gypsum (Darton, 1906a,b; Condit, 1917; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Dinwoody Formation includes silty shale and siltstone, with limestone, dolomite, and gypsum in the upper part (Lowry et al., 1976; Libra et al., 1981). Although the Chugwater Group or Formation and the Dinwoody Formation are confining units for the underlying Paleozoic aquifer system, both formations may yield small quantities of water to wells and springs from interbedded limestones, gypsum beds, and sandstones at some locations in the BHB (Libra et al., 1981; Western Water Consultants, Inc., 1983b; Jarvis, 1986). Little hydrogeologic information is available describing the Chugwater-Dinwoody aquifer and confining unit, but well-

yield and spring-discharge measurements and other hydraulic properties for both hydrogeologic units composing the confining unit are summarized on **Plate IX**.

Chemical characteristics

Groundwater-quality data are presented and described for both the Chugwater aquifer and Dinwoody confining unit composing the Chugwater–Dinwoody aquifer and confining unit in this section of the report.

7.2.6.1 Chugwater aquifer

The chemical composition of groundwater in the Chugwater aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from seven wells and six springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram I). TDS concentrations were variable and indicated that most waters were slightly saline (77 percent of samples) and the remaining waters were fresh (**Appendix E2; Appendix G2**, diagram I; supplementary data tables). TDS concentrations ranged from 251 to 2,840 mg/L, with a median of 1,960 mg/L.

The chemical composition of groundwater in the Chugwater aquifer also was characterized and the quality evaluated on the basis of 99 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram E). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny; however, the concentrations indicated that most of the waters were very saline (43 percent) (**Appendix F2; Appendix H2**, diagram E; supplementary data tables). TDS concentrations ranged from 1,170 to 57,500 mg/L, with a median of 24,100 mg/L.

Concentrations of some properties and constituents in the Chugwater aquifer in the BHB 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 infrequently exceeded health-based standards (USEPA MCLs and HALs): nitrate plus nitrite (8 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (92 percent), sulfate (85 percent), and pH (8 percent below lower limit).

Most available water-quality analyses for the Chugwater aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), sulfate (98 percent), chloride (90 percent), and pH (6 percent above upper limit). TDS concentrations in 68 percent of produced-water samples from the Chugwater aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Chugwater aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (92 percent), TDS (46 percent), and selenium (33 percent). Values of one property (pH) were greater than livestock-use standards (8 percent below lower limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (98 percent), TDS (95 percent), and chloride (92 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (83 percent), sulfate (70 percent), chloride (69 percent), and pH (6 percent above upper limit).

7.2.6.2 Dinwoody confining unit

The chemical composition of groundwater in the Dinwoody confining unit in the BHB was characterized and the quality evaluated on the basis of one produced-water sample from a well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (8,590 mg/L) indicated that the water was moderately saline.

Concentrations of some properties and constituents in water from the Dinwoody confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample with few chemical analyses of properties and constituents; thus, comparisons between concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had available health-based standards (USEPA MCLs and HALs), so no comparisons could be made. The produced-water sample had concentrations of one property (TDS) and two constituents (chloride and sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. The produced-water sample had concentrations of two constituents (chloride and sulfate) that exceeded agricultural-use standards. The

produced-water sample had concentrations of one property (TDS) and one constituent (chloride) that exceeded livestock-use standards.

7.2.7 Paleozoic aquifer system

The Paleozoic aquifer system in the BHB includes lithostratigraphic units ranging in age from lower Ordovician to Permian or Lower Triassic(?). The upper boundary of the aquifer system is unclear and subject to different interpretations by different investigators **(Plate III)**. The differences are attributable to contradictory hydrogeologic classification of the intertonguing facies of the Permian and Lower Triassic-age Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation), and to different interpretations of the amount of hydraulic connection between these formations and the underlying Tensleep aquifer, described in detail under "Goose Egg–Phosphoria aquifer and confining unit" in the Wind River Basin, **Section 7.1.12** of this report. The Paleozoic aquifer system defined herein comprises four hydrogeologic units – the Goose Egg–Phosphoria aquifer and confining unit, Tensleep aquifer, Amsden confining unit, and Madison–Bighorn aquifer **(Plate III)**. The Paleozoic aquifer system is defined herein as being confined above by overlying low-permeability shales and siltstones of the Chugwater–Dinwoody confining unit and below by thick, low-permeability shales of the Gallatin–Gros Ventre confining unit **(Plate III)**.

The Tensleep and Madison–Bighorn aquifers are the most developed aquifers in the Paleozoic aquifer system. Both aquifers are considered "major" or "principal" aquifers because some wells at some locations can yield hundreds to thousands of gallons per minute. Consequently, the aquifers have been developed for domestic, public-supply, irrigation, or stock use in the BHB. Both aquifers also are extensively utilized for petroleum production, typically in the numerous anticlines rimming the basins proper.

The groundwater quality of aquifers contained in the Paleozoic aquifer system varies greatly throughout the BHB. Recharge to these units generally occurs where the formations crop out near basin margins. Near recharge areas, water in these aquifers may be relatively fresh and suitable for most uses. This is where most domestic, public-supply, irrigation, or stock wells are completed. Elsewhere, and with increasing depth (as indicated primarily by produced-water samples) and as the water moves away from outcrop into the basin interior, the water may have high TDS concentrations (be highly mineralized) and not suitable for most uses or only marginally suitable for livestock and other uses. Only oil or gas wells are completed in deeply buried Paleozoic hydrogeologic units.

7.2.7.1 Goose Egg–Phosphoria aquifer and confining unit

The physical and chemical characteristics of the Goose Egg–Phosphoria aquifer and confining unit in the BHB are described in this section of the report.

Physical characteristics

The Goose Egg–Phosphoria aquifer and confining unit hydrogeologic unit comprises the Permian and Lower Triassic-age Goose Egg Formation and the Permian-age Phosphoria and Park City Formations **(Plate III)**. The Goose Egg Formation is an evaporite sequence consisting of gypsiferous siltstone, mudstone, and silty shale; its thickness ranges from 100 to 300 ft (Sheldon, 1963). Sheldon noted intertonguing between the Park City and Goose Egg Formations. Sheldon considered the Park City Formation representative of a western facies and the Goose Egg Formation representative of an eastern facies, their boundary located at the longitude of Worland in Washakie County. The Phosphoria Formation is considered equivalent to the Goose Egg Formation (Cooley, 1986a; Plafcan et al., 1993). The Park City Formation is a cherty dolomitic carbonate sequence with a thickness ranging from 25 to 325 ft (Sheldon, 1963). Overall, the formations have generally low permeability, except where lithology is favorable or faults and fractures are present (Stone, 1967). With the exception of oil wells, relatively few wells are installed in the Goose Egg–Phosphoria aquifer and confining unit, and development is limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Most information describing the formations composing the hydrogeologic unit is from oil field data.

The complex intertonguing and interfingering relation between carbonate facies, siltstone facies, and shale and evaporate facies in the Goose Egg–Phosphoria aquifer and confining unit creates numerous small permeable zones that can function as individual aquifers (or subaquifers) or provide hydraulic connection with the underlying Tensleep aquifer (Libra et al., 1981; Cooley, 1986a; Jarvis, 1986; Spencer, 1986a). Consequently, the Goose Egg–Phosphoria aquifer and confining unit can be considered a sequence of rocks that function as both aquifer (some carbonate and evaporite sequences) and confining or leaky confining unit (siltstone, evaporite, and shale sequences), and that definition is used herein **(Plate III)**. Nonetheless, some investigators believe that there is enough hydraulic connection with the underlying Tensleep aquifer that the three formations (or parts of the three formations) can be considered part of the Tensleep aquifer, at least in parts of the BHB **(Plate III)**. The different interpretations of the hydraulic function of the three formations can be seen in the numerous and commonly different hydrogeologic unit classifications **(Plate III)**. Recharge to these units is likely from infiltration of precipitation and streamflow in outcrop areas, interformational flow in fractures along anticlines, and possibly by infiltration of water from overlying saturated alluvium (Berry and Littleton, 1961; Lowry et al., 1976). Discharge from these units is likely to seeps, springs, streams, and interformational movement

(Berry and Littleton, 1961; Lowry et al., 1976). Well-yield and spring-discharge measurements and other hydraulic properties for the hydrogeologic unit are summarized on **Plate IX**; most of these data are from wells or drill-stem tests associated with petroleum extraction from the Phosphoria Formation.

Chemical characteristics

Groundwater-quality data are presented and described for the Goose Egg aquifer and confining unit and the Phosphoria aquifer and confining unit.

7.2.7.1.1 Goose Egg aquifer and confining unit

The chemical composition of groundwater in water from the Goose Egg aquifer and confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells and two springs. Individual constituent concentrations are listed in Appendix E2. TDS concentrations were variable and indicated that most waters were fresh (83 percent of samples) and the remaining waters were slightly saline (Appendix E2; Appendix G2, diagram J; supplementary data tables). TDS concentrations ranged from 205 to 2,690 mg/L, with a median of 397 mg/L.

Concentrations of some properties and constituents in water from the Goose Egg aquifer and confining unit in the BHB 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 a health-based standard (USEPA MCLs and HALs): boron (100 percent of samples analyzed for the constituent). Concentrations of one property and two constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (33 percent), TDS (33 percent), and fluoride (8 percent).

Concentrations of some properties and constituents in water from the Goose Egg aquifer and confining unit exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Two constituents and one property in environmental water samples had concentrations greater than agricultural-use standards: boron (100 percent), sulfate (33 percent), and TDS (17 percent). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

7.2.7.1.2 Phosphoria aquifer and confining unit

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in Appendix E2. TDS concentrations were highly variable and indicated that some waters were slightly saline (40 percent of samples) and the remaining waters were fresh to briny (Appendix E2; supplementary data tables). TDS concentrations ranged from 787 to 49,400 mg/L, with a median of 2,840 mg/L.

The chemical composition of groundwater in the Phosphoria aquifer and confining unit also was characterized and the quality evaluated on the basis of 505 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram F). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny; however, the concentrations indicated that most of the waters were moderately saline (59 percent) (**Appendix F2; Appendix H2**, diagram F; supplementary data tables). TDS concentrations ranged from 1,080 to 220,000 mg/L, with a median of 7,200 mg/L.

Concentrations of some properties and constituents in water from the Phosphoria aquifer and confining unit in the BHB 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 (USEPA MCLs and HALs): boron (67 percent of samples analyzed for the constituent) and fluoride (33 percent). Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), filtered iron (100 percent), fluoride (67 percent), chloride (60 percent), and pH (33 percent below lower limit). TDS concentrations in 20 percent of environmental water samples from the Phosphoria aquifer and confining unit exceeded State of Wyoming Class IV standards.

Most water-quality analyses available for the Phosphoria aquifer and confining unit were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): strontium (100 percent of samples analyzed for the constituent) and barium (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (98 percent), chloride (79 percent), filtered iron (75 percent), and pH (3 percent below lower limit and 6 percent above upper limit). TDS concentrations in 31 percent of produced-water samples from the Phosphoria aquifer and confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (100 percent), TDS (80 percent), boron (67 percent), chloride (60 percent), and SAR (25 percent). The properties and constituents that had concentrations greater than livestock-use standards were pH (33 percent below lower limit), boron (33 percent), chloride (20 percent), and TDS (20 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (98 percent), TDS (97 percent), chloride (91 percent), filtered iron (25 percent), lithium (8 percent), and pH (less than 1 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (73 percent), sulfate (50 percent), chloride (23 percent), and pH (3 percent below lower limit and 6 percent above upper limit).

7.2.7.2 Tensleep aquifer

The physical and chemical characteristics of the Tensleep aquifer in the BHB are described in this section of the report.

Physical characteristics

The Tensleep aquifer is a major aquifer in the BHB. The aquifer is used primarily as a source of water for domestic, stock, and (rarely) irrigation purposes along the eastern margin of the BHB, where the hydrogeologic units composing the aquifer are exposed at land surface (crop out) or are at shallow depths (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). Large volumes of water also are withdrawn from the numerous oilfields developed, mostly on anticlines, throughout the basin (Western Water Consultants, Inc., 1982a,b; Cooley, 1986a; Doremus, 1986).

Most wells flow at land surface under artesian pressure, except near some outcrops associated with anticlines, where unconfined conditions exist (Horn, 1963; Cooley, 1984, 1986a; Hinckley et al., 1982a). Flowing wells located along the BHB margin may yield large and dependable supplies of potable water, especially those located near anticlines, but reported well and spring yields vary considerably **(Plate IX)**. Water in the aquifer generally is under artesian pressure, with wellhead pressures generally less than 50 pounds per square inch (psi) in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported the same wellhead pressures as Cooley did in outcrop areas and wellhead pressures ranging from 200 to 5,000 psi in the basin interior.

The Tensleep aquifer comprises the Pennsylvanian-age Tensleep Sandstone and Ranchester Limestone Member of the Amsden Formation (Cooley, 1984, 1986a; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Some investigators also include the overlying Permian and Lower Triassic-age Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) as part of the aquifer, but note that hydraulic connection between the hydrogeologic units is dependent on the absence of local confining units (low permeability lithologies) and on the extent of fracture-enhanced permeability associated with folds and faults (Western Water Consultants, Inc., 1982a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Thus, the upper boundary (and associated upper confining unit) of the aquifer is subject to different interpretations among the various investigators. The Tensleep aquifer is defined herein as being confined above by overlying low-permeability shales and siltstones of the overlying Goose Egg-Phosphoria aquifer and confining unit hydrogeologic unit **(Plate III)**; however, the overlying Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) may be in hydraulic connection with (and considered part of) the aquifer at some locations where folding and faulting and associated fracturing allows for hydraulic connection of these units (Western Water Consultants, Inc., 1982a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). The aquifer is confined below by shales of the underlying Horseshoe Shale Member of the Amsden Formation (Cooley, 1984, 1986a; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. The Horseshoe Shale Member corresponds to the Amsden aquifer, as described in a following section.

The Tensleep Sandstone is composed of predominantly tan, cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica (Todd, 1963; Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Love at al., 1993; Plafcan et al., 1993). Cherty dolomite in the upper part and discontinuous marine limestone and dolomite (carbonates) in the lower part of the formation were reported by Moore (1984). Porosity and permeability in the Tensleep Sandstone are primarily intergranular, and decrease with secondary cementation and recrystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966). Fractures and solution processes (in carbonate-rich zones) may enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976). Interstitial porosity decreases from the eastern basin margin to the basin interior (and with increasing depth) due to precipitation of dolomite and silica (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966; Fox et al., 1975). Secondary fracture porosity and permeability are common in folds and faults in the BHB, and these locations have the best potential for groundwater development (Western Water Consultants, Inc., 1982a,b; Jarvis, 1986; Spencer, 1986a).

The Ranchester Limestone Member of the Amsden Formation is composed primarily of limestone. The geologic unit is not permeable everywhere; Jarvis (1986a, p. 37) noted that the

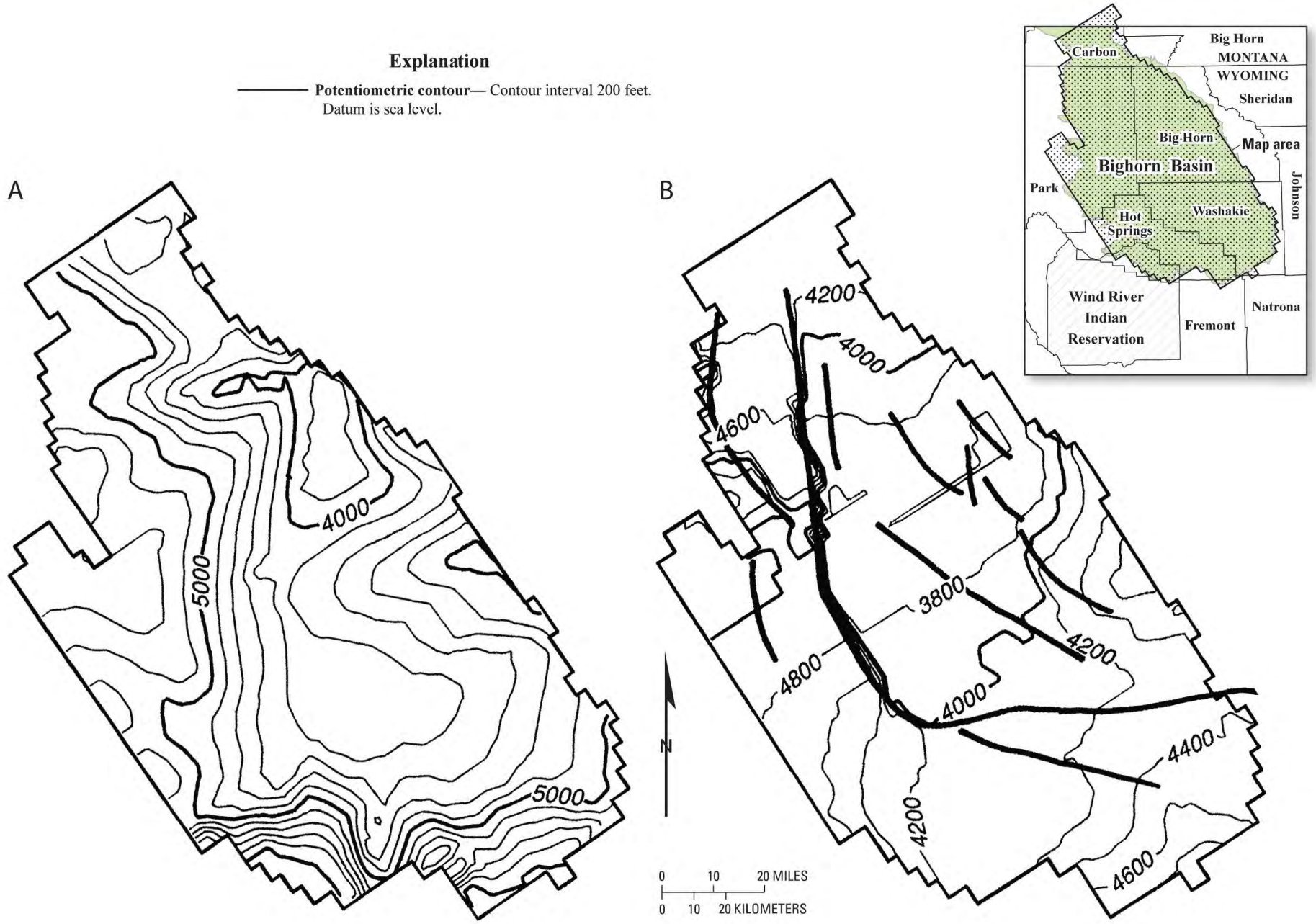


Figure 7-10. Comparison of predevelopment potentiometric surfaces, Tensleep aquifer, Bighorn Basin, Wyoming (modified from Bredehoeft et al., 1992, Figures 7 and 8). A, Bredehoeft and Bennett's (1971) predevelopment potentiometric map for the Tensleep aquifer. B, Haun's (1988) predevelopment potentiometric map for the Tensleep aquifer. Heavy lines indicate major faults.

unit is "probably impermeable except where limestones have been dolomitized."

Numerous potentiometric surfaces of the Tensleep aquifer in the BHB have been constructed because of its importance as a petroleum reservoir and its utility as a model of artesian basins in the Wyoming foreland. Predevelopment potentiometric surfaces of the aquifer have been constructed by Todd (1963), Bredehoeft and Bennett (1972), and Haun (1984). These investigators based their potentiometric surfaces exclusively on hydraulic-head data from the Tensleep Sandstone and did not include hydraulic-head data from the underlying Ranchester Limestone Member of the Amsden Formation or the overlying Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) (as described above, these last geologic units are considered part of the aquifer by several investigators). The potentiometric surface constructed by Bredehoeft and Bennett (1972) has been widely reproduced and discussed since publication (and is reproduced herein on **Plate XII**). The potentiometric surfaces of Todd (1963) and Bredehoeft and Bennett (1972) are fairly similar, and both neglect the effects of faulting; both maps show groundwater flowing uniformly from outcrops along the basin margins (recharge areas) to the deep, central parts of the basin. The potentiometric-surface map constructed by Haun (1984) differs from that of Bredehoeft and Bennett (1972). In addition to hydraulic head, Haun utilized oilfield tilts from Zapp (1956) and, more importantly, included faults as barriers to lateral groundwater flow. Consequently, the interpretations of the predevelopment potentiometric surfaces of the Tensleep aquifer **(Figure 7-10)** are substantially different (Bredehoeft et al., 1992). Bredehoeft et al. (1992, p. 535) noted that Haun (1984) minimized higher outcrop elevations as control, and also noted that hydraulic potentials were several hundred feet lower than those of Bredehoeft and Bennett's (1972) potentiometric surface. By examining the various hydraulic factors that affect construction of potentiometric surfaces, Bredehoeft et al. (1992) concluded that major faults can act as both barriers and vertical conduits for regional flow, and that major fault zones control regional Paleozoic aquifer groundwater flow in the BHB. This led them to conclude that the hydraulic heads presented in both Tensleep aquifer predevelopment potentiometric surface maps are likely "too low over much of the basin" (Bredehoeft et al., 1992, p. 545).

The potentiometric surface of the Tensleep aquifer in the northeastern BHB was mapped by Western Water Consultants, Inc. (1982a, Plate 4; 1982b, Plate 4; 1983c, Plate 4). These maps were based on hydraulic-head data from the Tensleep Sandstone and overlying Phosphoria Formation. (The Phosphoria Formation and equivalent Park City Formation are considered part of the Tensleep aquifer by several investigators.) The general direction of groundwater flow is from outcrop areas along the eastern basin margin toward the basin interior. Large cones of depression were associated with the Byron, Garland, Sage Creek, Deaver, and Frannie oilfields (Western Water Consultants, Inc., 1982a,b). Drawdown at the Manderson and Bonanza oilfields was hypothesized (Western Water Consultants, Inc., 1983c). Discontinuity of the potentiometric surface near the Manderson anticline was noted and attributed to a fault acting as a partial barrier to groundwater flow (Western Water Consultants, Inc., 1983c).

Detailed mapping of the potentiometric surface of the Tensleep aquifer was conducted in the southeastern BHB by Jarvis (1986, Plate 4) and southwestern BHB by Spencer (1986a, Plate 4). Cooley (1986a) mapped the potentiometric surface of the aquifer in the Tensleep area [a small part of the same area mapped by Jarvis (1986a)]. The potentiometric-surface maps of Jarvis (1986, Plate 4) and Spencer (1986a, Plate 4) were meant to complement one another, and both maps have been combined into a single potentiometric-surface map for this study on **Plate XIII**. The investigators accounted for the many effects of folding and faulting on interpretation of the potentiometric surface, incorporating and expanding upon the improved understanding of hydraulic interconnection between recharge areas along Wyoming structural basin margins and deep central basins provided by Huntoon (1985a). The potentiometric-surface maps of the Tensleep aquifer constructed by Jarvis and Spencer are the most detailed available for any aquifer in the BHB, and the effects of these numerous structures on the potentiometric surface of the Tensleep aquifer can be seen on **Plate XIII**.

Chemical Characteristics

Groundwater-quality data are presented and described for only one lithostratigraphic unit (Tensleep Sandstone) included in the Tensleep aquifer. Groundwater-quality data for the underlying Ranchester Limestone Member of the Amsden Formation are included in the description of the Amsden aquifer because groundwater samples from the Amsden aquifer generally were only associated with the Amsden Formation, not the three members composing it.

The chemical composition of groundwater in the Tensleep aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 38 wells and six springs. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram K). Summary statistics calculated for available constituents are listed in Appendix E2. TDS concentrations were variable and indicated that most waters were fresh (82 percent of samples) and the remaining waters were slightly to moderately saline (Appendix E2; Appendix G2, diagram K; supplementary data tables). TDS concentrations ranged from 156 to 3,750 mg/L, with a median of 259 mg/L.

Concentrations of some properties and constituents in water from the Tensleep aquifer in the BHB 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 infrequently exceeded health-based standards (USEPA MCLs and HALs): fluoride (2 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (100 percent exceeded lower limit), TDS (27 percent), sulfate (23 percent), filtered iron (21 percent), fluoride (15 percent), pH (3 percent below lower limit), and chloride (2 percent).

The chemical composition of groundwater in the Tensleep aquifer also was characterized and the quality evaluated on the basis of 504 produced-water samples from wells. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram G). Summary statistics calculated for available constituents are listed in Appendix F2. TDS concentrations from produced-water samples were highly variable and ranged from fresh to very saline; however, the concentrations indicated that most of the waters were moderately saline (61 percent) (Appendix F2; Appendix H2, diagram G; supplementary data tables). TDS concentrations ranged from 324 to 33,700 mg/L, with a median of 3,650 mg/L.

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one constituent that exceeded health-based standards (USEPA MCLs and HALs): strontium (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (100 percent), manganese (100 percent), TDS (99 percent), sulfate (96 percent), chloride (38 percent), and pH (1 percent below lower limit and 4 percent above upper limit). TDS concentrations in 6 percent of produced-water samples from the Tensleep aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (26 percent), TDS (14 percent), chloride (7 percent), boron (5 percent), and filtered iron (5 percent). One property (pH) had values greater than a livestock-use standard (3 percent below lower limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (97 percent), TDS (89 percent), chloride (60 percent), filtered iron (50 percent), and pH (less than 1 percent below lower limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (28 percent), sulfate (21 percent), pH (1 percent below lower limit and 4 percent above upper limit), and chloride (2 percent).

Jarvis (1986) noted two types of water in the Tensleep aquifer. Calcium-bicarbonate-type waters were predominant near the basin margin, whereas calcium-sulfate-type waters were predominant in the basin interior. Jarvis also attributed large concentrations of sodium, calcium, sulfate, and chloride in water from the Tensleep aquifer to anhydrite dissolution. Evaluation of a much larger number of groundwater samples compiled for this study indicates that ionic composition (water type) clearly changes with increasing TDS concentration (Appendix G2, diagram K; Appendix H2, diagram G). Groundwaters from the Tensleep aquifer classified as fresh or slightly saline generally were calcium-bicarbonate and calcium-magnesium-bicarbonate type, whereas waters classified as moderately to very saline generally were classified as (and evolve toward) sodium-sulfate type.

7.2.7.3 Amsden confining unit

The physical and chemical characteristics of the Amsden confining unit in the BHB are described in this section of the report.

Physical characteristics

The Amsden confining unit in the Bighorn Basin is composed of the Horseshoe Shale Member of the Middle and Lower Pennsylvanian and Upper Mississippian-age Amsden Formation (Jarvis, 1986; Spencer, 1986a). The Horseshoe Shale Member confines and separates the underlying Madison–Bighorn aquifer from the overlying Tensleep aquifer **(Plate III)**. The reported thickness of the entire Amsden Formation, including all three members, ranges from about 120 to 300 ft in the BHB (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Most hydrogeologic data for the Amsden confining unit are assigned to the Amsden Formation, not individual members; consequently, well-yield and spring-discharge measurements and other hydraulic properties for the entire formation are summarized on **Plate IX**, even though some measurements may be from the Ranchester Limestone and Darwin Sandstone Members, which are included in the Tensleep and Madison aquifers, respectively **(Plate III)**.

Chemical characteristics

Groundwater-quality samples from the Amsden confining unit

are described in this section. Groundwater-quality data for the Amsden confining unit are assigned to the Amsden Formation, not individual members; consequently, groundwater-quality for the entire formation are summarized, even though some measurements may be from the Ranchester Limestone and Darwin Sandstone Members. The chemical composition of groundwater in the Amsden confining unit in the BHB was characterized and the quality evaluated on the basis of 21 produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F2. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram H). TDS concentrations from produced-water samples were highly variable and ranged from fresh to briny; however, concentrations indicated most of the waters were moderately saline (52 percent) (Appendix F2; Appendix H2; supplementary data tables). TDS concentrations ranged from 590 to 53,500 mg/L, with a median of 3,280 mg/L.

Concentrations of some properties and constituents in water from the Amsden confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one constituent that exceeded health-based standards (USEPA MCLs and HALs): strontium (50 percent of samples analyzed for the constituent). The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (95 percent), chloride (52 percent), and pH (15 percent above upper limit). TDS concentrations in 10 percent of produced-water samples from the Amsden confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. The produced-water samples generally had concentrations of two constituents and one property that exceeded agricultural-use standards: sulfate (95 percent), chloride (76 percent), and TDS (76 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (24 percent), sulfate (14 percent), chloride (10 percent), and pH (5 percent above upper limit).

7.2.7.4 Madison–Bighorn aquifer

The physical and chemical characteristics of the Madison–Bighorn aquifer in the BHB are described in this section of the report.

Physical Characteristics

The Madison–Bighorn aquifer is a major aquifer in the BHB, and includes the Madison, Darby, and Bighorn aquifers. The Madison–Bighorn aquifer is used as a source of water for domestic, stock, irrigation, and public supply purposes along the eastern margin of the BHB, where lithostratigraphic units composing the aquifer are exposed at land surface or at shallow depth (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). Flowing wells located along the mountain-basin margin may yield large and dependable supplies of potable water, especially those located near anticlines. Water in the aquifer may be under high artesian pressure, with wellhead pressures ranging from 150 to 250 psi in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported the same wellhead pressures as Cooley (1986a) did in outcrop areas, and 600 to 4,900 psi in the basin interior. The aquifer is an important source of public water supply for numerous communities in the BHB. Large volumes of water also are withdrawn from the numerous oilfields developed, mostly in anticlines, throughout the basin (Doremus, 1986).

The Madison–Bighorn aquifer includes the Mississippian-age Madison Limestone (containing the Madison aquifer), the Upper Devonian-age Darby, Three Forks, and Jefferson Formations (containing the Darby aquifer), and the Ordovician-age Bighorn Dolomite (containing the Bighorn aquifer) **(Plate III)**. These formations are hydraulically connected by solution-enlarged joints and fractures (Cooley, 1986a; Doremus, 1986). The Madison–Bighorn aquifer is confined above by low-permeability shales and carbonates of the Amsden Formation (namely the Horsehoe Shale Member) and below by the Gallatin–Gros Ventre confining unit (Stone, 1967; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Several investigators (Libra et al., 1981; Western Water Consultants, Inc., 1982a) consider the Three Forks and Jefferson Formations (considered eastern BHB equivalents of the Darby Formation) to be local confining or leaky confining units between the Bighorn Dolomite and Madison Limestone in parts of the BHB **(Plate III)**. The Madison–Bighorn aquifer is composed of predominantly thick-bedded limestone and dolomite with minor interbedded siltstone and some chert (Cooley, 1986a). The aquifer thickness is highly variable, and depends on the thickness and degree of hydraulic connection between the various lithostratigraphic units composing the aquifer. The Madison Limestone may be cavernous in outcrop. Carbonate beds within the Jefferson Formation are potentially productive in areas with fracturing (Western Water Consultants, Inc., 1983b).

Although hydraulic head may be hundreds of feet greater than that in overlying hydrogeologic units such as the Tensleep aquifer, and although the aquifer generally is confined above by the overlying Amsden Formation and below by the underlying

Gallatin–Gros Ventre confining unit, the Madison–Bighorn aquifer may be in local hydraulic connection with overlying and underlying aquifers at some locations in the BHB. On the basis of the similarity of reservoir fluids in many BHB oilfields, Lawson and Smith (1966) suggested hydraulic connection between geologic units composing the aquifer with overlying geologic units as a result of extensive vertical fracturing in Paleozoic rocks. Stone (1967) also noted the similarity of reservoir fluid chemistry and hydraulic heads in many eastern BHB oilfields, and suggested that faulting and fracturing of Paleozoic rocks in parts of the BHB could provide hydraulic connection with overlying geologic units (for example, Tensleep Sandstone) at some locations. Cooley (1986a, p. 5) noted that these types of vertical fractures appear to allow for "vertical water movement through the upper part of the Amsden Formation from the Madison–Bighorn aquifer to the Tensleep Sandstone near Ten Sleep and Big Trails, where there are anomalous small differences between their potentiometric surfaces." He also noted possible vertical movement of water from underlying aquifers: "The potentiometric contours of the Madison–Bighorn aquifer indicate a slight hydraulic mound near Zeisman dome, and this indicates that there may be some upward movement of water through the Gallatin Limestone and Gros Ventre Formations from the Flathead Sandstone along fractures associated with the doming" (Cooley, 1986a, p. 5). Furthermore, hydraulic continuity of the Madison–Bighorn aquifer can be interrupted in the interior basin by fault-cored anticlines overlying deep basin thrust faults (Huntoon, 1985a; Doremus, 1986). Extensional fractures on fold crests also may increase permeability and vertical hydraulic connection between overlying and underlying aquifers (Doremus, 1986). All these investigators essentially concluded that vertical fracturing associated with anticlines may propagate upward through overlying Paleozoic rocks and damage the hydraulic integrity of aquifers and confining units, allowing for movement of fluids between some Paleozoic formations (implying aquifers) in parts of the BHB.

Permeability in the limestones and dolomites composing the Madison–Bighorn aquifer is both primary and secondary, but the presence of water in the aquifer is controlled primarily by secondary permeability. Primary permeability is minor and attributable to interclast and intercrystalline porosity, whereas secondary permeability predominates due to fractures associated with folds and faults, joints, solution features/cavities, caves, paleokarst, and bedding-plane partings (Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986, and references therein; Spencer, 1986a). Much of this secondary permeability development is attributable to fractures and associated solution enhancement structurally induced by the folding and faulting of brittle carbonates (Huntoon, 1976; Vietti, 1977; Doremus, 1986).

Permeability characteristics of the Madison–Bighorn aquifer differ between mountain-basin margins and basin interior. Fracture permeability in outcrops along the edges of the eastern basin margin is enhanced by the dissolution of carbonates through infiltration of precipitation (recharge) (Doremus, 1986; Huntoon, 1985a,b, 1993). Permeability decreases basinward as distance from the tectonically fractured Bighorn Mountains and basin margin increases (Bredehoeft, 1964; Huntoon, 1985b, 1993; Doremus, 1986). These investigators note that permeability decreases basinward due to "less fracture permeability in undeformed parts of the basin interior, decreasing solution enhancement of fractures basinward, and re-precipitation of cements in deeper parts of the basin" (Doremus, 1986, p. IV-15). Doremus also noted that solution enhancement of fractures decreases basinward because hydraulic gradients decrease as distance away from recharge areas increases, and carbonate solubility decreases as temperatures increase within the basin interior.

Potentiometric-surface maps of the Madison–Bighorn aquifer in the northeastern BHB were constructed for the same geographic area by Western Water Consultants, Inc. (1982a, Figure 7) and Doremus (1986, Figure 13). The map constructed by Doremus is reproduced herein as **Plate XIV**. Both Western Water Consultants, Inc. and Doremus identified three primary components of regional groundwater flow in the northeastern BHB. The investigators stated that groundwater within the Madison-Bighorn aquifer moves (1) north and northeast into the mapped study area from the southern and western parts of the basin, (2) south from recharge areas in the southern Pryor Mountains, and (3) west and northwest from recharge areas for the Madison aquifer along the western flank of the Bighorn Mountains **(Plate XIV)**. Regional groundwater flow converges on potentiometric-surface depressions associated with large withdrawals and resulting hydraulic head declines in producing oilfields (for example, Byron and Garland oilfields, **Plate XIV**) and springs located in the basin interior (Western Water Consultants, Inc., 1982a; Doremus, 1986). The low hydraulic heads associated with the Byron and Garland anticlines and corresponding oilfields are due to not only fluid withdrawals from the petroleum reservoirs, but also to interformational leakage in fracture and fault zones in the crests of the anticlines (Doremus, 1986). Hydraulic gradients decrease from 300 feet per mile near recharge areas to 30 feet per mile within the basin interior (Doremus, 1986).

The potentiometric surface constructed by Doremus (1986) shows that faults and folds (anticlines) substantially affect groundwater flow in the Madison–Bighorn aquifer and alter the configuration of the potentiometric surface in the northeastern BHB **(Plate XIV)**. Faults may act as barriers to groundwater flow in areas where structural offset is large enough to juxtapose an aquifer against confining units, effectively severing aquifer hydraulic continuity (Western Water Consultants, Inc.,

1982a; Huntoon, 1985a; Doremus, 1986). Groundwater also flows along the structural strikes of various anticlines in the northeastern BHB due to "extensional fractures developed in the crests of these anticlines" that "provide zones of secondary enhanced fracture permeabilities which serve as favored hydraulic conduits between recharge areas and the interior of the basin" (Doremus, 1986, p. 36). Doremus also noted that movement between recharge areas and these anticlines was evidenced by the similar water chemistry in anticlines and springs in the recharge areas. In contrast, groundwater flow in other parts of the northeastern BHB may not be continuous from "unsevered recharge areas to the basin interior because faults coring basin anticlines are often barriers to groundwater flow" (Doremus, 1986, p. 37).

Cooley (1986a, Plate 4) constructed a potentiometric-surface map of the Madison–Bighorn aquifer in the Ten Sleep area of the southeastern BHB (reproduced herein as **Plate XV**). Groundwater flow is generally westward in the mapped area, with the steepest gradient adjacent to the Bighorn Mountains. Cooley (1986a) reported that, similarly to the northeastern BHB, the potentiometric surface of the Madison–Bighorn aquifer in the Ten Sleep area also is affected substantially by folds and faults, as well as by withdrawals associated with oilfields. Low hydraulic heads were identified near Big Trails, Ten Sleep, and Hyattville as a result of groundwater discharge from Paleozoic aquifers to shallower aquifers or to the surface.

Well-yield and spring-discharge measurements and other hydraulic properties for the Madison, Darby, and Bighorn aquifers composing the Madison–Bighorn aquifer are summarized in **Plate IX**. Much of the hydraulic data is from petroleum drill-stem tests. These tests typically are conducted in petroleum fields located along the crest of anticlines where fracture zones occur; consequently, values of hydraulic properties in these areas may be higher than those in undeformed parts of the aquifer.

Chemical characteristics

Doremus (1986) evaluated the regional groundwater-quality of the Madison–Bighorn aquifer in the northeastern BHB by examining the factors that affect the quality of groundwater in the aquifer as it moves from recharge areas into the basin interior. TDS concentrations are generally lowest near outcrop areas (assumed recharge areas) and become higher in the basin interior. Doremus concluded that four factors were responsible for changes in groundwater chemistry as water moves from recharge areas along the basin margin into the basin interior: (1) aquifer severing by large basin faults that disrupt the hydraulic continuity of the aquifer and are barriers to groundwater flow from nearby recharge areas; (2) interformational mixing of waters in fracture zones developed in the crests of anticlines; (3) mixing with mineralized waters (large TDS concentrations) from the southern BHB; and (4) movement of groundwater beneath petroleum traps along basin anticlines.

Groundwater-quality data are presented and described for the three aquifers (Madison, Darby, and Bighorn aquifers) composing the Madison–Bighorn aquifer. No data were available to evaluate the groundwater-quality characteristics of the Three Forks and Jefferson Formations, so data for the Darby aquifer is from the Darby Formation. The Darwin Sandstone is included in the Amsden Formation chemical characteristics discussion, above.

7.2.7.4.1 Madison aquifer

The chemical composition of groundwater in the Madison aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 37 wells and 11 springs. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram L). Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (90 percent of samples) and the remaining waters were slightly to moderately saline (**Appendix E2; Appendix G2**, diagram L; supplementary data tables). TDS concentrations ranged from 173 to 9,980 mg/L, with a median of 232 mg/L.

Concentrations of some properties and constituents in water from the Madison aquifer in the BHB 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 several properties and constituents exceeded health-based standards (USEPA MCLs and HALs): gross alpha radioactivity (17 percent of samples analyzed for the constituent), radium-226 plus radium-228 (17 percent), lead (12 percent of samples), boron (8 percent), and fluoride (5 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (25 percent), TDS (12 percent), sulfate (10 percent), fluoride (8 percent), pH (3 percent below lower limit), and chloride (2 percent).

The chemical composition of groundwater in the Madison aquifer also was characterized and the quality evaluated on the basis of 201 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram I). TDS concentrations from produced-water samples were highly variable and ranged from fresh to briny, and the concentrations indicated that most of the water was moderately saline (55 percent) (**Appendix F2; Appendix H2**, diagram I; supplementary data tables). TDS concentrations ranged from 319 to 142,000 mg/L, with a median of 3,370 mg/L.

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of two constituents that always exceeded health-based standards (USEPA MCLs and HALs): fluoride (100 percent) and strontium (100 percent). The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: fluoride (100 percent), filtered iron (100 percent), TDS (99 percent), sulfate (95 percent), chloride (47 percent), and pH (6 percent below lower limit and 3 percent above upper limit). TDS concentrations in produced-water samples from the Madison aquifer rarely exceeded the State of Wyoming Class IV standard (2 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (17 percent), radium-226 plus radium-228 (17 percent), sulfate (10 percent), boron (8 percent), TDS (7 percent), SAR (4 percent), and chloride (2 percent). The properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (17 percent), radium-226 plus radium-228 (17 percent), pH (3 percent below lower limit), TDS (2 percent), and sulfate (2 percent).

The produced-water samples from the Madison aquifer generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (96 percent), chloride (84 percent), TDS (83 percent), filtered iron (50 percent), and pH (1 percent above upper limit). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (8 percent), chloride (5 percent), pH (6 percent below lower limit and 3 percent above upper limit), and sulfate (3 percent).

7.2.7.4.2 Darby aquifer

The chemical composition of groundwater in the Darby aquifer in the BHB was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations from both produced-water samples (3,280 and 6,760 mg/L) indicated that the waters were moderately saline (**Appendix F2**).

Concentrations of some properties and constituents in water from the Darby aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one property and two constituents that exceeded aesthetic standards (USEPA MCLs and HALs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), and chloride (50 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Both produced-water samples had concentrations of one property (TDS) and two constituents (chloride and sulfate) that exceeded agricultural-use standards. Concentrations of TDS and sulfate exceeded livestock use standards in one of the two produced-water samples.

7.2.7.4.3 Bighorn aquifer

The chemical composition of groundwater in the Bighorn aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (83 percent of samples) and the remaining waters were moderately saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 136 to 3,410 mg/L, with a median of 230 mg/L.

Concentrations of some properties and constituents in water from the Bighorn aquifer in the BHB 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 (USEPA MCLs and HALs): boron (17 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (20 percent below lower limit and 20 percent above upper limit), TDS (17 percent), chloride (17 percent), fluoride (17 percent), and sulfate (17 percent).

The chemical composition of groundwater in the Bighorn aquifer also was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, and the concentrations indicated that most waters were moderately saline (55 percent) (**Appendix F2; Appendix H2**, Figure J; supplementary data tables). TDS concentrations ranged from 1,180 to 14,300 mg/L, with a median of 3,460

mg/L.

Most water-quality analyses available for the Bighorn aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had available USEPA MCLs or HALs, so comparisons could not be made to health-based standards. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), chloride (73 percent), and pH (11 percent below lower limit). TDS concentrations in produced-water samples from the Bighorn aquifer infrequently exceeded State of Wyoming Class IV standards (9 percent).

Concentrations of some properties and constituents in environmental water samples exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were chloride (17 percent), sulfate (17 percent), TDS (17 percent), and boron (17 percent). Values of one characteristic were greater than the livestock-use standard: pH (20 percent below lower limit and 20 percent above upper limit).

The produced-water samples generally had concentrations of one property and two constituents that always or frequently exceeded agricultural-use standards: sulfate (100 percent), TDS (91 percent), and chloride (82 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (18 percent), pH (11 percent below lower limit), chloride (9 percent), and sulfate (9 percent).

7.2.7.5 Recharge, discharge, and groundwater movement

Aquifers in the Paleozoic aquifer system in the BHB are recharged primarily from precipitation (rain and snow melt) and streamflow infiltrating exposed outcrops along the BHB mountain-basin margin (Lowry et al., 1976; Libra et al., 1981; Cooley, 1984, 1986a; Huntoon, 1985a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). Upturned beds of Paleozoic rocks are common, and substantial differences in streamflow losses or gains have been observed between karst and non-karst areas (Huntoon, 1985a,b; Plafcan et al., 1993). In the Trapper-Medicine Lodge area between Shell and Hyattville, some streams reportedly lose all flow to underlying karst developed in the Madison-Bighorn aquifer (Huntoon, 1985a,b). Streamflow data from Druse et al. (1989) led Plafcan et al. (1993) to conclude that recharge to Paleozoic aquifers from streams was variable along the western flank of the Bighorn Mountains. Plafcan et al. (1993, p. 49) also speculated that "in non-karst areas, direct infiltration of precipitation into outcrops is probably a more substantial recharge component than that contributed by losing streams."

Potentiometric-surface maps presented previously herein indicate that groundwater in the Paleozoic aquifers generally flows away from the outcrop areas (source of recharge) on the basin margins and toward the center of the BHB (Bighorn Basin). Groundwater near the Bighorn River flows northward toward Montana on some maps. Many investigators speculate that groundwater flow in other aquifers in the BHB is similar to flow in the Tensleep aquifer (for example, Lowry et al., 1976; Libra et al., 1981; Cooley, 1984, 1986a; Huntoon, 1985a). However, much of the water that enters the aquifers as recharge does not move into the basin: the homocline from the Bighorn Mountains to the BHB is discontinuous due to numerous thrust and high-angle coring reverse faults (Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a; Huntoon (1985a,b,c, 1993; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). These coring faults, commonly associated with anticlines, can disrupt hydraulic continuity of the aquifers along the basin-mountain margin. This faulting may create hydraulically unconnected groundwater systems in the foot and hanging walls where permeable rocks are faulted against impermeable rocks, and thus prevent movement of water into the basin interior.

The work of Huntoon (1985a), as well as the published work of his graduate students (Doremus, 1986; Jarvis, 1986; Spencer, 1986a) and contemporary investigators (Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a), represents greatly improved understanding of the effects of folding and faulting on groundwater flow in Paleozoic aquifers (Tensleep and Madison–Bighorn aquifers) of the BHB – improved understanding that is applicable to aquifers in other Wyoming structural basins (see Huntoon, 1993). Collectively, these investigators noted that the numerous folds and faults located along the eastern homoclinal BHB margin, depending upon their spatial orientation, may act as (1) hydraulic conduits that connect recharge areas along the basin margin to the basin interior if oriented oblique to basin margins, or (2) act as hydraulic barriers that sever the hydraulic continuity between recharge areas along the basin margin and basin interior if oriented parallel to basin margins (depending on the amount of fault displacement). These investigators also noted that areas with tight folding and extensive faulting commonly have enhanced secondary permeability from fractures and may yield greater volumes of water than undeformed areas, an advancement subsequently exploited by those attempting to locate high-yielding public-supply wells in the Paleozoic aquifer system in the BHB. In addition, these investigators noted that groundwater quality in the Paleozoic aquifer system varies relative to location along folds and faults, as well as to proximity to the basin margin. Groundwater within the

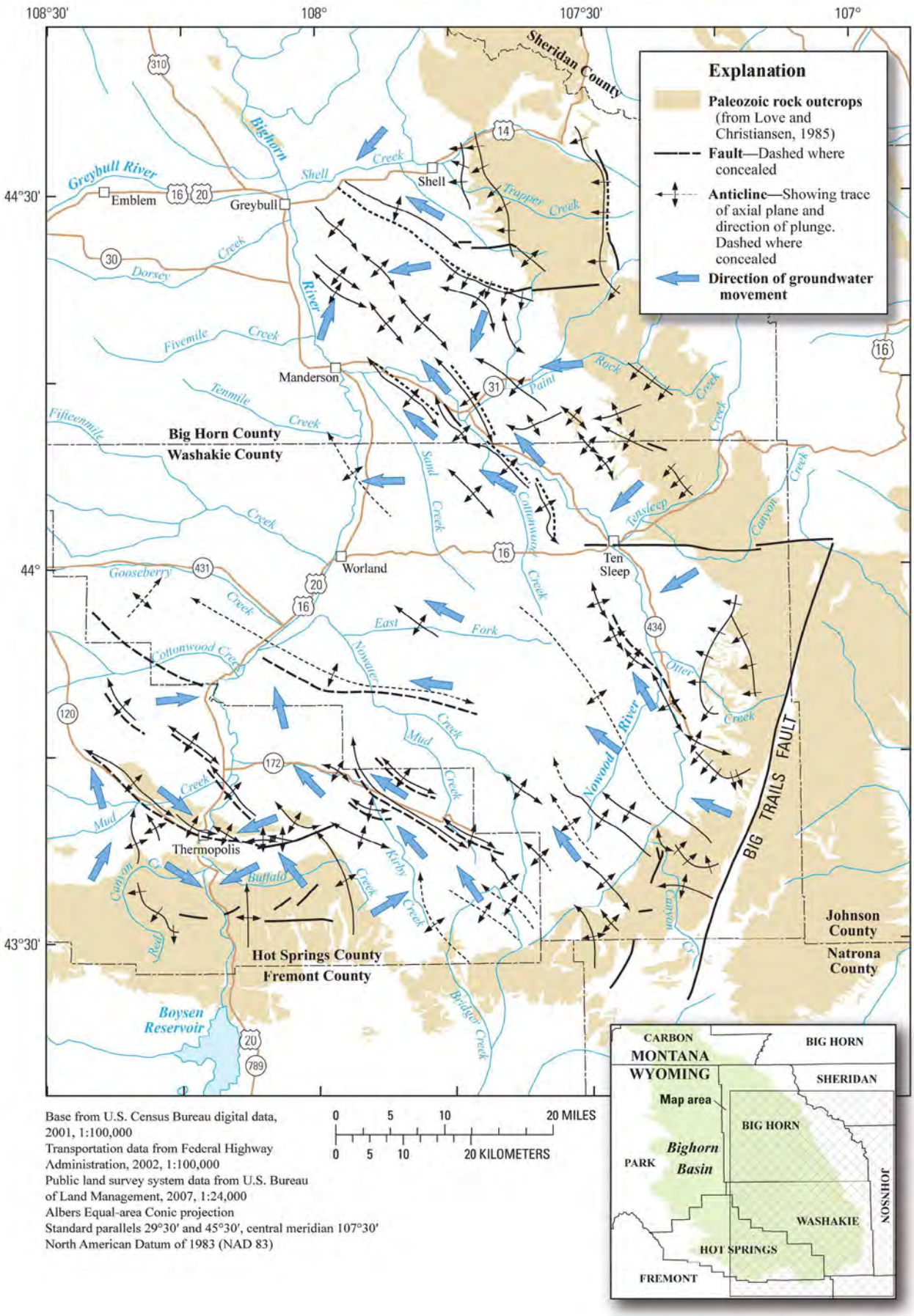


Figure 7-11. Generalized groundwater movement for the Paleozoic aquifer system in the Bighorn Basin, Wyoming (modified from Jarvis, 1986a, Figure 18).

footwalls of fault-severed anticlines is generally of poor quality, whereas groundwater in the hanging wall is generally of good quality (or at least better than in the footwall). Groundwater quality near outcrops along basin margins (assumed to represent recharge areas) is generally good and generally becomes poor (more mineralized) as the water moves into the basin interior.

Jarvis (1986, Figure 18) used this improved understanding to graphically show how generalized groundwater flow in Paleozoic aquifers in the BHB is structurally controlled by folding and faulting (modified herein as **Figure 7-11**). Groundwater flows around lateral terminations of faults oriented parallel to the basin margin, whereas groundwater flows along and parallel to structural trends oriented oblique to the basin margin **(Figure 7-11)**. In addition, major coring reverse faults sever hydraulic conductivity between recharge areas (represented by outcrop areas) and the basin interior.

Discharge from aquifers in the Paleozoic aquifer system is both natural and anthropogenic. The Tensleep aquifer predevelopment (prior to oilfield development) potentiometric-surface map of Bredehoeft and Bennett (1972) indicates discharge at outcrops along the Bighorn River (Lowry et al., 1976; Plafcan et al., 1993). The Bighorn River has cut through numerous anticlines in the basin interior, resulting in natural discharge from now-exposed Paleozoic rocks (Libra et al., 1981; Egemeier, 1973; Lowry et al., 1976; Plafcan et al., 1993). For example, Lowry et al. (1976, Sheet 1) noted that the Bighorn River has "eroded completely through the Tensleep Sandstone at the Wyoming-Montana border," and "therefore, water does not move northward out of Wyoming in the Tensleep Sandstone." Thermal springs from the Madison-Bighorn and (or) Tensleep aquifers reportedly discharge from the Sheep Mountain, Little Sheep Mountain, and Thermopolis/Warm Springs anticlines (Libra et al., 1981; Egemeier, 1973; Plafcan et al., 1993). Libra et al. (1981) reported spring flows from Paleozoic rocks along the Rattlesnake Mountain anticline west of Cody. Discharge from the Paleozoic aquifers in the Nowood River area was reported by Cooley and Head (1979b); they reported that water from the Tensleep aquifer moves upward along solution-collapse features in Phosphoria Formation evaporites and discharges as seeps and springs or as recharge to Quaternary unconsolidated alluvial deposits overlying the Phosphoria Formation. Other points of natural discharge from aquifers in the Paleozoic aquifer system include numerous springs and gaining streams. The primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are large-capacity public-supply, irrigation, and oilfield wells (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a; Plafcan et al., 1993).

7.2.8 Gallatin–Gros Ventre confining unit

The physical and chemical characteristics of the Gallatin–Gros Ventre confining unit in the BHB are described in this section of the report.

Physical characteristics

The Gallatin–Gros Ventre confining unit is composed of the Cambrian-age Gallatin Limestone and Gros Ventre Formation. The thick unit confines and separates the underlying Flathead aquifer from the overlying Madison-Bighorn aquifer **(Plate III)**. The reported thickness of the confining unit ranges from about 800 to 1,200 ft (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Gallatin Limestone is composed of glauconitic gray-green shale and pebbly limestone with minor interbedded sandstone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Gros Ventre Formation is composed of glauconitic and sandy limestone with interbedded gray-green shale, sandy limestone, and uncommon interbedded limy sandstone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Although both formations are confining units for aquifers in the Paleozoic aquifer system, both may yield small quantities of water to wells and springs at some locations in the BHB, especially from interbedded limestones and sandstones (Libra et al., 1981; Jarvis, 1986). Little hydrogeologic information is available describing the Gallatin–Gros Ventre confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for the Gallatin and Gros Vertre confining units are summarized on **Plate IX**.

Chemical characteristics

No groundwater samples were available to evaluate the groundwater-quality characteristics of the Gallatin confining unit. The chemical composition of groundwater in the Gros Ventre confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations for those samples are listed in Appendix E2. TDS concentrations indicated that water from the spring (210 mg/L) was fresh, whereas water from the well (3,010 mg/L) was moderately saline.

Concentrations of some properties and constituents in the Gros Ventre Formation in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use with the exception of the boron concentration in the well sample. Concentrations of one property (TDS) and four constituents (chloride, fluoride, filtered iron, and sulfate) exceeded aesthetic standards (USEPA SMCLs) for domestic use in the water sample from the well.

Concentrations of a few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. One property (TDS) and two constituents (chloride and sulfate) in the environmental water sample from the well had concentrations greater than agricultural-use standards. No property or constituent had concentrations that exceeded State of Wyoming livestock standards.

7.2.9 Flathead aquifer

The physical and chemical characteristics of the Flathead aquifer are described in this section of the report.

Physical characteristics

The Flathead aquifer is composed of the Cambrian-age Flathead Sandstone **(Plate III)**. The Flathead aquifer is a major aquifer in the BHB. The Flathead Sandstone consists of fine- to medium-grained arkosic and quartzitic sandstone with some interbedded shale in the upper part (Libra et al., 1981; Cooley, 1986a). The Flathead aquifer is confined above by thick low-permeability shales of the overlying Gallatin–Gros Ventre confining unit and below by nonporous igneous and metasedimentary rocks of the Precambrian basement that act as a basal confining unit to all aquifers and aquifer systems in the BHB (Stone, 1967; Vietti, 1977; Libra et al., 1981; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. The aquifer is a source of water for stock and irrigation purposes along the eastern margin of the BHB, where the Flathead Sandstone is exposed at land surface or at shallow depth (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). The Flathead Sandstone ranges from 100 to 200 ft in thickness, but is absent in the northeastern BHB (Lowry et al., 1976; Cooley, 1986a).

Water in the Flathead aquifer may be under very high artesian pressure, with wellhead pressures reportedly as high as 472 psi in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported wellhead pressures of greater than 400 psi in outcrop areas, and wellhead pressures ranging from 2,600 to 3,200 psi in the basin interior. Flowing wells located along the mountain-basin margin may yield large and dependable supplies of potable water. Cooley (1986a) noted decreased shut-in pressure for wells completed in the aquifer near Ten Sleep, and he attributed the decreases to continuous discharge of water from wells completed in the aquifer. Although considered a potentially very good source of groundwater for development by most investigators, the aquifer is rarely developed as a source of water because of deep burial throughout most of the BHB.

Porosity is intergranular, but secondary permeability is present as a result of fracturing near folds and faults (Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). In fact, Cooley (1986a, p. 4) stated that "water movement in the sandstone seems to be controlled principally by fracturing, judging from the general tightness of the unfractured part of the sandstone where exposed." Recharge to the Flathead aquifer is likely from infiltration of precipitation and streamflow in outcrop areas. Well-yield and spring-discharge measurements and other hydraulic properties for the Flathead aquifer are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Flathead aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from eight wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram M). TDS concentrations were variable and indicated that waters were fresh (**Appendix E2; Appendix G2,** diagram M; supplementary data tables). TDS concentrations ranged from 58 to 443 mg/L, with a median of 163 mg/L.

The chemical composition of groundwater in the Flathead aquifer also was characterized and the quality evaluated on the basis of 13 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram K). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline; however, concentrations indicated that most waters were moderately saline (69 percent) (**Appendix F2; Appendix H2,** diagram K; supplementary data tables). TDS concentrations ranged from 2,730 to 13,300 mg/L, with a median of 3,950 mg/L.

Concentrations of some properties and constituents in the Flathead aquifer in the BHB 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 (USEPA MCLs and HALs): barium (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (20 percent), manganese (20 percent), pH (8 percent above upper limit), and aluminum (6 percent exceeded lower and upper limits).

Most water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had a concentration of two constituents in one sample that exceeded health-based standards (USEPA MCLs and HALs):

radium-226 plus radium-228 and strontium. The produced-water samples had concentrations of several properties and constituents that always exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (100 percent), and sulfate (100 percent). TDS concentrations in 15 percent of produced-water samples from the Flathead aquifer exceeded State of Wyoming Class IV standards.

Concentrations of a few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. The constituent and property in environmental water samples that had concentrations greater than agricultural-use standards were chromium (100 percent) and SAR (9 percent). Values of one property were greater than livestock-use standards: pH (8 percent above upper limit).

The produced-water samples had concentrations of two constituents and one property that always exceeded agricultural-use standards: chloride (100 percent), sulfate (100 percent), and TDS (100 percent). The produced-water samples had concentrations of one characteristic and one constituent that infrequently exceeded livestock-use standards: TDS (15 percent) and chloride (15 percent).

7.2.10 Precambrian basal confining unit

The physical and chemical characteristics of the Precambrian basal confining unit in the BHB are described in this section of the report.

Physical characteristics

Undifferentiated nonporous igneous and metasedimentary rocks of the Precambrian basement act as a basal confining unit to the Flathead aquifer, as well as to all aquifers and aquifer systems in the BHB (Stone, 1967; Vietti, 1977; Libra et al., 1981; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Little is known about Precambrian rocks at depth in the BHB; however, wells are completed locally for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out – permeability is attributable to weathered, fractured, or faulted rocks (Lowry et al., 1976; Libra et al., 1981). Lowry et al. (1976) noted that the shallow permeable zone typically is less than 100 ft deep. The investigators also noted that fractures decrease in both size and number with depth. Well-yield and spring-discharge measurements and other hydraulic properties for the Precambrian basal confining unit are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Precambrian basal confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations indicated that the waters were fresh (**Appendix E2**; supplementary data tables). On the basis of the few properties and constituents analyzed for, water from Precambrian rocks in the BHB was suitable for most uses. Concentrations of one constituent and one property exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (50 percent of samples analyzed for the constituent) and pH (33 percent above upper limit). Concentrations of one property exceeded State of Wyoming standards for agricultural use: pH (33 percent above upper limit). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

7.3 Absaroka Range and Yellowstone Volcanic Area

The physical and chemical characteristics of aquifers in the Absaroka Range and Yellowstone volcanic area (AYV) are described in this section of the report.

Physical characteristics

The AYV (generally the "Absaroka–Yellowstone volcanics" of **Figure 7-1**, Quaternary aquifers within them, and the Tertiary, Mesozoic, and Paleozoic aquifers just east of them) is sparsely populated and has no major population centers. Much of the area is within the boundary of Yellowstone National Park. Consequently, the demand for water supply generally is small, and is limited to visiting tourists, park employees, and residents of areas surrounding the park. Because the population is dispersed, much of this demand is met with groundwater. However, aquifers that can provide a water supply sufficient in quantity and quality may not be present at many locations.

Three types of aquifers are present in the AYV – Quaternary unconsolidated-deposit aquifers, Quaternary and Tertiary volcanic-rock aquifers, and Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers (Lowry and Gordon, 1964; Cox, 1973b, 1976). The areal extents of lithostratigraphic units composing these hydrogeologic units are shown on **Plate I**. These aquifers are utilized primarily for domestic or public supply use. Many of the Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers are buried beneath Quaternary-age unconsolidated deposits and Quaternary and Tertiary-age volcanic rocks. Most wells are completed in Quaternary unconsolidated-deposit aquifers in the AYV, and few, if any, wells are completed in the Quaternary and Tertiary volcanic-rock aquifers even though they crop out throughout most of the area (Cox, 1976). Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers are rarely utilized for water supply, and little or no information is available describing their hydrogeologic characteristics within the AYV.

Quaternary unconsolidated-deposit aquifers in the AYV are composed typically of alluvium (and colluvium), lacustrine

deposits, or glacial deposits (Cox, 1976). Landslide deposits are saturated in some locations and yield water to numerous springs (Cox, 1976). Locally, Quaternary unconsolidated-deposit aquifers commonly overlie Quaternary and Tertiary volcanic-rock aquifers and likely are in direct hydraulic connection with them (Whitehead, 1996). Groundwater in Quaternary unconsolidated-deposit aquifers typically is unconfined. Many wells completed in Quaternary unconsolidated-deposit aquifers in the Yellowstone National Park area are located close to and along streams or lakes (Cox, 1973b, 1976). Such aquifers commonly are in hydraulic connection with and receive recharge from the adjacent stream or lake (Cox, 1973b, 1976). Well-yield and spring-discharge measurements for unconsolidated deposits in the AYV (alluvial aquifers, aquifers in landslide deposits, aquifers in lacustrine deposits, glacial-deposit aquifers) are summarized on **Plate IX**.

Quaternary and Tertiary volcanic-rock aquifers are composed of extrusive igneous rocks (primarily basalt and rhyolite) and beds of tuff and volcanic ash. These aquifers are essentially undeveloped; with the exception of spring discharges, little or no quantitative hydrogeologic information is available to characterize and evaluate the development potential of these aquifers **(Plate IX)**. Investigations related to these aquifers have been mainly of thermal waters and related features in Yellowstone National Park (Ball, McCleskey, et al., 2002; Ball, Nordstrom, Cunningham, et al., 1998; Ball, Nordstrom, Jenne, and Vivit, 1998; Ball, Nordstrom, McCleskey, et al., 2001; Bargar, 1978; Fix, 1949; Fournier, Christianson, et al., 1994, Fournier and Morgenstern, 1971; Fournier and Rowe, 1966; Fournier and Truesdell, 1970; Friedman and Norton, 1982, 1990; Gooch and Whitfield, 1888; Merler, 1964; Marler and White, 1975; Morey et al., 1961; Pearson and Truesdell, 1978; Rowe, Fournier, and Morey, 1965, 1973; Rye and Truesdell, 1993; Schlundt and Moore, 1909; Stauffer, Jenne, and Ball, 1980; Stauffer and Thompson, 1978, 1984; Stearns, Stearns, and Waring, 1937; Thompson and Hutchinson, 1981; Thompson, Presser, et al., 1975; Thompson and Sandhya, 1979; Truesdell and Fournier, 1976a,b; Truesdell, Nathenson, and Rye, 1977; Truesdell, Rye, et al., 1978; Truesdell and Thompson, 1982; Weed, 1889; White, 1991; White, Hutchinson, and Keith, 1988). Cox (1976, Sheet 1) speculated on the potential well yield of the various Quaternary and Tertiary volcanic-rock aquifers 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). 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." Well-yield and spring-discharge measurements for Quaternary and Tertiary volcanic-rock aquifers in the AYV are summarized on **Plate IX**.

Chemical characteristics

The chemical characteristics of Quaternary unconsolidated-deposit aquifers, Quaternary and Tertiary volcanic-rock aquifers, and Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers in the AYV are described in the following sections.

7.3.1 Quaternary unconsolidated-deposit aquifers

The chemical characteristics of Quaternary unconsolidated-deposit aquifers (alluvial aquifers, aquifers in lacustrine deposits, and glacial-deposit aquifers) in the AYV are described in this section of the report. Groundwater-quality samples from springs discharging from aquifers in landslide deposits and hydrothermal deposits also are described.

Alluvial aquifers

The chemical composition of groundwater in alluvial aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 33 wells and 5 springs. Summary statistics calculated for available constituents are listed in **Appendix E3.** Major-ion composition in relation to TDS is shown on a trilinear diagram **(Appendix G3**, diagram A). TDS concentrations were variable and indicated that most waters were fresh (89 percent of samples) and the remaining waters were slightly saline (Appendix E3; Appendix G3, diagram A; supplementary data tables). TDS concentrations ranged from 57 to 1,550 mg/L, with a median of 182 mg/L.

Concentrations of some properties and constituents in water from alluvial aquifers in the AYV 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 (USEPA MCLs and HALs): arsenic (60 percent of samples analyzed for the constituent), fluoride (42 percent), antimony (40 percent), boron (14 percent), molybdenum (11 percent), lead (10 percent), and nitrate plus nitrite (9 percent). Concentrations of some properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (58 percent exceeded lower limit), fluoride (54 percent), pH (34 percent below lower limit and 3 percent above upper limit), manganese (25 percent), filtered iron (20 percent), TDS (18 percent), and chloride (11 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were arsenic (30 percent), SAR (21 percent), lithium (18 percent), manganese (15 percent), chloride (13 percent), boron (21 percent), pH (3 percent below lower limit and 3 percent above upper limit), and filtered iron (3 percent). Properties and constituents that had concentrations greater

than livestock-use standards were pH (34 percent below lower limit and 3 percent above upper limit), arsenic (30 percent), and boron (14 percent).

Aquifers in landslide deposits

The chemical composition of water from aquifers in landslide deposits in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (158 mg/L) indicated that the water was fresh. On the basis of the properties and constituents analyzed, the quality of water from landslide deposits in the AYV was suitable for most uses. No properties or constituents had concentrations that approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Aquifers in lacustrine deposits

The chemical composition of water from aquifers in lacustrine deposits in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 38 wells. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram B). TDS concentrations were variable and indicated that waters were fresh (**Appendix E3**; **Appendix G3**, diagram B; supplementary data tables). TDS concentrations ranged from 65 to 340 mg/L, with a median of 99.5 mg/L.

Concentrations of some properties and constituents in water from aquifers in lacustrine deposits in the AYV 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 a few constituents exceeded health-based standards (USEPA MCLs and HALs): arsenic (100 percent of samples analyzed for the constituent), nitrate plus nitrite (7 percent), and fluoride (5 percent). Concentrations of one property and several constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (16 percent below lower limit), manganese (16 percent), filtered iron (11 percent), and fluoride (8 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Concentrations of one constituent in environmental water samples were greater than an agricultural-use standard: manganese (5 percent). Values for one property were less than a livestock-use standard: pH (16 percent below lower limit).

Aquifers in hydrothermal deposits

The chemical composition of water from aquifers in hydrothermal deposits in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (568 mg/L) indicated that the water was fresh.

Concentrations of some properties and constituents in hydrothermal deposits in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The environmental water generally was suitable for domestic use. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (below lower limit), TDS, aluminum (exceeded lower and upper limits), manganese, and sulfate.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the AYV. Properties and constituents in the environmental water sample that had concentrations greater than agricultural-use standards were pH (below lower limit), SAR, aluminum, boron, and sulfate. One property (pH, below lower limit) and one constituent (aluminum) had concentrations greater than livestock-use standards.

Glacial-deposit aquifers

The chemical composition of groundwater in glacial-deposit aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 14 wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram C). TDS concentrations indicated that the waters were fresh (**Appendix E3; Appendix G3**, diagram C; supplementary data tables). TDS concentrations ranged from 112 to 933 mg/L, with a median of 223 mg/L.

Concentrations of some properties and constituents in the glacial-deposit aquifers in the AYV 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 a few constituents exceeded health-based standards (USEPA MCLs and HALs): ammonia (38 percent of samples analyzed for the constituent), nitrate plus nitrite (30 percent), and fluoride (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (100 percent), pH (53 percent below lower limit), fluoride (35 percent), filtered iron (29 percent), sulfate (6 percent), and TDS (6 percent).

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were manganese (88 percent), boron (14 percent), SAR (10 percent), filtered iron (7 percent), and sulfate (6 percent). Values for one property were less than a livestock-use standard: pH (53 percent below lower limit).

7.3.2 Quaternary and Tertiary volcanic-rock aquifers

The chemical characteristics of Quaternary and Tertiary volcanic-rock aquifers in rhyolite flows, tuff, and intrusive igneous rocks; the Yellowstone Group; and the Absaroka Volcanic Supergroup in the AYV are described in this section of the report.

7.3.2.1 Aquifers in rhyolite flows, tuff, and intrusive igneous rocks

The chemical composition of water from aquifers in rhyolite flows, tuff, and intrusive igneous rocks in the AYV was characterized and the quality evaluated on the basis of environmental water samples from one test hole and nine springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram D). TDS concentrations indicated that waters were fresh (**Appendix E3; Appendix G3**, diagram D; supplementary data tables). TDS concentrations ranged from 40 to 808 mg/L, with a median of 93 mg/L.

Concentrations of some characteristics and constituents in water from aquifers in rhyolite flows, tuff, and intrusive igneous rocks in the AYV 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 (MCLs and HALs): fluoride (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: fluoride (100 percent of samples analyzed for the constituent), pH (60 percent below lower limit), aluminum (17 percent exceeded lower and upper limits), manganese (12 percent), chloride (10 percent), and TDS (10 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were lithium (12 percent), SAR (12 percent), and chloride (10 percent). Values for one property (pH) were less than livestock-use standards (60 percent below lower limit).

7.3.2.2 Yellowstone Group aquifers

The chemical composition of groundwater in the Yellowstone Group aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from two wells, one test hole, and 23 springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram E). TDS concentrations were variable and indicated that most waters were fresh (62 percent of samples) and the remaining waters were slightly saline (**Appendix E3; Appendix G3**, diagram E; supplementary data tables). TDS concentrations ranged from 43 to 2,130 mg/L, with a median of 563 mg/L.

Concentrations of some properties and constituents in water from the Yellowstone Group aquifers in the AYV 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 (USEPA MCLs and HALs): boron (50 percent of samples analyzed for the constituent), arsenic (47 percent), molybdenum (33 percent), antimony (28 percent), and beryllium (4 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (69 percent below lower limit), aluminum (66 percent above lower limit and 23 percent above upper limit), TDS (50 percent), chloride (38 percent), filtered iron (19 percent), manganese (15 percent), and sulfate (8 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were boron (50 percent), chloride (46 percent), SAR (42 percent), arsenic (32 percent), lithium (27 percent), pH (15 percent below lower limit), TDS (12 percent), manganese (12 percent), sulfate (8 percent), aluminum (5 percent), and filtered iron (4 percent). Properties and constituents that had concentrations greater than livestock-use standards were pH (69 percent below lower limit), arsenic (32 percent), boron (32 percent), and aluminum (5 percent).

7.3.2.3 Absaroka Volcanic Supergroup aquifers

The chemical composition of groundwater in the Absaroka Volcanic Supergroup aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from two wells and eight springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram F). TDS concentrations indicated that waters were fresh (**Appendix E3**; **Appendix G3**, diagram F; supplementary data tables). TDS

concentrations ranged from 101 to 265 mg/L, with a median of 176 mg/L.

Concentrations of some properties and constituents in water from the Absaroka Volcanic Supergroup aquifers in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (50 percent of samples analyzed for the constituent exceeded lower and (or) upper limits). No properties or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.3.3 Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers

The chemical characteristics of groundwater in Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers in the AYV are described in this section of the report. Most of the groundwater-quality data from these aquifers were obtained from produced-water samples collected from wells located along the periphery of the AYV outside areas of volcanic rocks (**Figure 7-1**: Tertiary, Mesozoic, and Paleozoic aquifers just east of the Absaroka–Yellowstone volcanics).

7.3.3.1 Willwood aquifer

The chemical composition of groundwater in the Willwood aquifer in the AYV was characterized and the quality evaluated on the basis of environmental water samples from three wells. Summary statistics calculated for available constituents are listed in **Appendix E3**. TDS concentrations indicated that the waters were fresh. TDS concentrations ranged from 220 to 398 mg/L, with a median of 326 mg/L.

Concentrations of some properties and constituents in water from the Willwood aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based (USEPA MCLs and HALs) and agricultural standards, all waters were suitable for domestic and agricultural use. Values of one property exceeded aesthetic standards (USEPA SMCLs) for domestic use and standards for livestock use: (pH) (33 percent of samples analyzed for the property had values above upper limits for domestic and livestock use).

7.3.3.2 Frontier aquifer

The chemical composition of groundwater in the Frontier aquifer in the AYV was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3**. TDS concentrations from produced-water samples indicated that the waters were slightly saline. TDS concentrations ranged from 1,420 to 1,870 mg/L, with a median of 1,800 mg/L.

Concentrations of some properties and constituents in water from the Frontier aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and one constituent that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the characteristic) and chloride (33 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples generally had concentrations of two constituents that exceeded agricultural-use standards: chloride (67 percent) and sulfate (33 percent). No properties or constituents had concentrations that exceeded livestock-use standards.

7.3.3.3 Cloverly aquifer

The chemical composition of groundwater in the Cloverly aquifer in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (1,850 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in water from the Cloverly aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between sample concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of one property (TDS) and one constituent (sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Few concentrations exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had a concentration of one constituent

(sulfate) that exceeded the agricultural-use standard. None of the concentrations in the produced water sample exceeded livestock-use standards.

7.3.3.4 Morrison confining unit and aquifer

The chemical composition of groundwater in the Morrison confining unit and aquifer in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (1,390 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in water from the Morrison confining unit in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between sample concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of two properties (pH and TDS) and one constituent (sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had concentrations of one constituent (sulfate) that exceeded agricultural-use standards and values of one property (pH) above the livestock-use standard.

7.3.3.5 Chugwater aquifer

The chemical composition of groundwater in the Chugwater aquifer in the AYV was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, diagram A). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, and most waters were very saline (73 percent) (**Appendix F3; Appendix H3**, diagram A; supplementary data tables). TDS concentrations ranged from 1,600 to 32,800 mg/L, with a median of 13,100 mg/L.

Concentrations of some properties and constituents in water from the Chugwater aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and two constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), and chloride (82 percent). TDS concentration in 73 percent of the produeced-water samples from the Chugwater aquifer exceeded the State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples generally had concentrations of two constituents and one property that exceeded agricultural-use standards: chloride (100 percent), sulfate (100 percent), and TDS (91 percent). The produced-water samples generally had concentrations of one property and two constituents that exceeded livestock-use standards: TDS (91 percent), sulfate (91 percent), and chloride (18 percent).

7.3.3.6 Phosphoria aquifer and confining unit

The chemical composition of groundwater in the Phosphoria aquifer in the AYV was characterized and the quality evaluated on the basis of 14 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, diagram B). TDS concentrations indicated that most waters were moderately saline (64 percent of samples) and the remaining waters were slightly saline (**Appendix F3; Appendix H3**, diagram B; supplementary data tables). TDS concentrations ranged from 1,050 to 8,850 mg/L, with a median of 3,810 mg/L.

Concentrations of some properties and constituents in water from the Phosphoria aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality samples were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and two constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (93 percent), and chloride (57 percent).

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples had concentrations of two constituents and one property that frequently exceeded agricultural-use standards: chloride (93 percent), sulfate (93 percent), and TDS (79 percent). The produced-water samples had concentrations of one property and one constituent that exceeded livestock-use standards: TDS (14 percent) and sulfate (14 percent).

7.3.3.7 Tensleep aquifer

The chemical composition of groundwater in the Tensleep aquifer in the AYV was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F3. TDS concentrations indicated that most waters were moderately saline (89 percent of samples) and the remaining waters were slightly saline (**Appendix F3**; supplementary data tables). TDS concentrations ranged from 1,060 to 7,950 mg/L, with a median of 4,570 mg/L.

Concentrations of some properties and constituents in water from the Tensleep aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality samples were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made.

The produced-water samples had concentrations of one property and two constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed the property), sulfate (89 percent), and chloride (44 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples had concentrations of two constituents and one property that exceeded agricultural-use standards: chloride (89 percent), sulfate (89 percent), and TDS (89 percent). The produced-water samples had concentrations of one characteristic and one constituent that exceeded livestock-use standards: TDS (22 percent) and sulfate (11 percent).

7.3.3.8 Amsden confining unit

The chemical composition of groundwater in the Amsden confining unit in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in Appendix F3. The TDS concentration (1,360 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in the Amsden confining unit in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in the produced-water sample and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water sample had a concentration of one property (TDS) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had concentrations of two constituents (chloride and sulfate) that exceeded agricultural-use standards. No concentrations exceeded State of Wyoming livestock standards.

7.3.3.9 Madison aquifer

The chemical composition of groundwater in the Madison aquifer in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations in the environmental water sample are listed in **Appendix E3**. The TDS concentration (138 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from the Madison aquifer in the AYV was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic,agriculture, or livestock water-quality standards.

Chapter 8

Groundwater Development and Use

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Groundwater development for beneficial purposes depends on quantity (in terms of "sustainable" yield), quality (acceptability for class of use), accessibility (technical and economic feasibility), and availability (freedom from legal or political constraints). The feasibility of groundwater development in any given area of the WBRB, depending on many technical, hydrogeologic, and cultural factors, ranges from unfeasible, through adequate for limited local use (stock and domestic), to sufficient for municipal, industrial, and agricultural use.

8.1 Information from previous and current water plans

Groundwater uses in the WBRB and the methods used to quantify them were described in the existing Statewide Framework Water Plan (WWC Engineering et al., 2007b), which compiled information from the BRS, Inc. et al. (2003) WBRB Water Plan and associated Technical Memoranda. Groundwater use information was updated in the current WBRB Water Plan (MWH et al., 2010a). The statistics and methods for estimating current and projected groundwater use from the 2003 and 2010 Plans are discussed, summarized, and compared in the 2010 Update Water Plan (MWH et al, 2010a, **Appendix A**); they are discussed briefly in this study. The 2003 Available Groundwater Determination Technical Memorandum to the 2003 Water Plan (Lidstone and Associates, 2003) summarized groundwater use in the WBRB as described in **Table 8-1**.

For this study the groundwater use statistics provided in the

Table 8-1. Total groundwater withdrawals by use (Lidstone and Associates, 2003).

Use	*Annual withdrawal (acre-feet/yr)*	*Estimation method*
Total permitted use	[1]**249,260**	12,381 WSEO permits as of 12/31/01
Agricultural wells	47,910	138 WSEO wells as of 12/31/01 (271.5 ac-ft/da × 153 da/yr) + 6,370 ac-ft/yr for stock watering
Industrial & mining	70,883 – 120,925	28.44% of WSEO permitted / WOGCC produced water in 2000
Municipal	4,344 – 9,819	Data on 36 community public systems provided by WWDC
Domestic/non-community	4,369 – 8,738	Rural population (26,002) × 150 to 300 gpcpd[2]
Recreational/environmental	5,366 + 4,635 =10,001	Method not described
Total	[1]**137,507 – 197,393**	The various methods described above

[1]Compare estimate by WSEO permits with estimates by other methods. [2]gallons per capita per day

Table 8-2a. WBRB water resources mass balance – precipitation, outflow, consumptive use (acre-feet) (MWH et al., 2010a).

Average annual water balance			
		Volume	***Percent of precipitation***
Total average annual precipitation		18,500,000	100%
Total average annual surface water outflow	–	6,800,000	36.8
Precipitation remaining in (Wyoming) WBRB	=	**11,700,000**	63.2
Average annual withdrawals and consumptive use[1]			
(Surface water and groundwater)		***Total withdrawals***	***Consumptive use***
Agriculture		3,136,728	1,079,971
Stock	+	6,370	6,370
Municipal/domestic	+	21,324	8,743
Recreational & environmental (groundwater)[2]	+	10,001	not significant
Industrial/mining	+	91,908	19,163
Evaporation from reservoirs	+	156,157	156,157
Totals	=	3,422,488	**(37.1%) 1,270,404**
Precipitation available for recharge and lost to evapotranspiration = precipitation – surface water outflow – total water consumed			**10,430,000 (56.4% of precipitation)**

[1]from MWH et al., 2010a, table 30
[2]from Lidstone and Associates, 2003

Table 8-2b. Ranges of estimated recharge and evapotranspiration – total and sedimentary aquifers (acre-feet)
[Precipitation available for recharge and evapotranspiration = Precipitation – surface water outflow – total water consumed = 10,430,000 acre-feet] [1]

Ranges (acre-feet)		***Percentages of available precipitation***
Available precipitation	10,430,000	***100%***
Total estimated WBRB recharge range[2]	3,024,575 – 6,498,237	29.0 – 62.3%
Total non-reservoir evapotranspiration range, by difference	7,405,021 – 3,931,359	71.0 – 37.7%
Estimated recharge range, sedimentary aquifers[2]	755,458 – 1,650,691	7.2 – 15.8%
Total non-reservoir evapotranspiration range, by difference	9,674,138 – 8,778,905	92.8 – 84.2%

[1] from Table 8-2a [2] from Table 6-9

Table 8-2c. Current annual groundwater withdrawals and consumptive use (MWH et al., 2010a).

Primary groundwater use categories	***Total withdrawals (acre-ft)***	***Consumptive (acre-ft)***	***Percent consumptive***
Agricultural – (irrigation & stock) (271.5 acre-ft/day from ~138 irrigation permitted wells for 153 days/year + 6,370 ac-ft for stock) *(Lidstone and Associates, 2003)*	47,910	20,660	43.1%
Municipal/community public water systems (39 community public water systems; 85 permitted wells)	+ [1]5,700	2,337	41%
Non-community systems (98 non-community public water systems)	+ [1]784	321	
Rural domestic (approximately 13,638 permitted wells)	+ 4,256 – [1]8,400	1,745 – 3,444	
Recreational & environmental (fish hatcheries, campgrounds, recreation facilities, etc.) *(Lidstone and Associates, 2003)*	+ 10,001	not significant	
Subtotal ranges	= **68,651 – 72,795**	**25,063 – 26,762**	**36.5 – 36.8%**
Annual industrial / mining groundwater withdrawals			
Fresh (self-supplied industrial)	224	39	17.4%
Fresh (mining)	+ 582	191	32.8%
Saline (mining)	+ 90,451	18,880	20.9%
Subtotal industrial & mining withdrawals	= **91,257**	**19,110**	20.9%
Total ranges	**160,000 – 164,000**	**44,000 – 46,000**	**27.6 – 28.0%**

[1] Municipal and domestic withdrawls (maximum) = 5,700 + 784 + 8,400 = 14,884 ac-ft

previous (BRS, Inc. et al., 2003; WWC Engineering et al., 2007b) and current (MWH et al., 2010a) Update WBRB Water Plans are compared with water balance calculations (MWH et al., 2010a) and the recharge estimates developed for this study **(Section 6.2.2).** Future groundwater requirement projections (MWH et al., 2010a) are also compared with these recharge estimates. **Tables 8-2a-f** summarize these interpretive calculations starting with the amount of water available for recharge and (non-reservoir) evapotranspiration after total consumptive (surface water and groundwater) uses and surface water outflow from the WBRB are subtracted from total precipitation **(Table 8-2a)**.

Precipitation is the ultimate source of all groundwater recharge. As presented in **Table 8-2a**, MWH et al. (2010a) estimated average annual precipitation in the WBRB as 18,500,000 acre-feet (ac-ft) and average annual outflow of surface water from the WBRB drainage basin as 6,800,000 acre-feet, leaving 11,700,000 acre-feet of precipitation remaining in the WBRB for non-consumptive and consumptive use and groundwater recharge. Subtracting consumptive use (estimated at 1,270,404 acre-feet, not including evapotranspiration) leaves 10,429,596 acre-feet of water available for recharge and evapotranspiration, which are numerically interdependent: As a range of recharge has been estimated **(Section 6.2.2, Table 6-9),** non-reservoir evapotranspiration can be directly estimated **(Table 8-2b)**.

Two cases are presented in **Table 8-2b** for estimated recharge

Table 8-2d. Summary of recharge estimates as percentages of water balance statistics, WBRB.

Average annual water balance statistics (acre-ft)[2]			*Recharge estimates (acre-ft)*[1]			
			Total		*Sedimentary aquifers*	
			Low 3,024,575	*High* 6,498,237	*Low* 755,458	*High* 1,650,691
A.	Total precipitation	18,500,000	16.3%	35.1%	4.1%	8.9%
B.	Precipitation remaining in basin (A minus outflow)	11,700,000	25.9%	55.5%	6.5%	14.1%
C.	Consumptive use, surface water, and groundwater	1,270,000	238.1%	511.5%	59.5%	129.9%
D.	Water available for recharge and evaporation (B minus C)	10,430,000	29.0%	62.3%	7.2%	15.8%

[1]Table 8-2b
[2]Table 8-2a

in the WRRB, (1) for total recharge over the entire drainage basin and (2) for recharge to only the sedimentary aquifers in the WBRB. As discussed in **Section 6.2.2**, because recharge to Precambrian crystalline and volcanic terrains at the highest elevations surrounding the WBRB is most likely discharged relatively quickly to surface waters, the estimates for recharge to only the sedimentary aquifers probably provides the better estimate for the overall water balance of the WBRB, with recharge amounting to approximately 7 to 16 percent of the amount of precipitation available to recharge and (non-reservoir) evapotranspiration combined. The range of evapotranspiration is estimated by subtracting the estimated range of recharge from the available precipitation (10,430,000 ac-ft).

Estimates for municipal, non-community public, rural domestic, industrial, and mining uses of groundwater were provided in the current WBRB Water Plan (MWH et al., 2010a). Estimates for agricultural, recreational and environmental uses of groundwater resources were provided in the previous Groundwater Determination (Lidstone and Associates, 2003).

Both total withdrawals and consumptive uses are summarized in **Table 8-2c** for the following use categories:

- Agricultural (irrigation and stock)
- Municipal (community public water systems)
- Non-community public water systems
- Rural domestic
- Recreation and environmental
- Industrial and mining (self-supplied fresh water)
- Mining (saline water – primarily oil and gas produced water)

Average annual groundwater withdrawals for the above primary uses are estimated at 159,908 to 164,052 acre-feet, and average annual consumptive use is estimated at 44,173 to 45,872 acre-feet (approximately 28% of total withdrawals). Water use categories, amounts, and estimation methods are discussed in detail later in this chapter.

Table 8-2d summarizes the high and low estimates for the two cases for recharge (total recharge and recharge to the sedimentary aquifers) in the WBRB as percentages of various water-balance statistics.

Table 8-2e. Summary of groundwater use estimates as percentages of recharge estimates.

Groundwater use estimates[2] (acre-ft)		*Recharge estimates (range, acre-ft)*[1]			
		Total WBRB		*Sedimentary aquifers*	
		Low 3,024,575	*High* 6,498,237	*Low* 755,458	*High* 1,650,691
Average annual groundwater withdrawals (high-end)	**164,000**	**5.4%**	**2.5%**	**21.7%**	**9.9%**
Agriculture	48,000	1.6%	0.7%	6.3%	2.9%
Municipal & domestic (high-end)	[3]15,000	0.5%	0.2%	2.0%	0.9%
Recreational & environmental	10,000	0.3%	0.2%	1.3%	0.6%
Industrial & mining	91,000	3.0%	1.4%	12.1%	5.5%
Average annual groundwater consumptive use (high-end)	**46,000**	**1.5%**	**0.7%**	**6.1%**	**2.8%**

[1]Table 8-2b [2]Table 8-2c [3]Table 8-2c, sum of municipal/community public water systems, non-community systems, and rural domestic systems (high-end) = 14,884 acre-feet.

Table 8-2f. Low, medium, and high estimates of future groundwater requirements and requirements as percentages of recharge to sedimentary aquifers at years 2020, 2040, 2060 [from MWH et al., 2010a].

Estimates of future annual groundwater requirements (acre-ft) *Demand case*	*Additional future requirements*			*Total future requirements*[2]		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
2020						
Municipal and domestic	130	210	680	15,014	15,094	15,564
Industrial and mining	22,750	35,020	40,460	114,007	126,277	131,717
2020 Total	22,880	35,230	41,140	129,021	141,371	147,281
2020 total requirements as percentages of high and low recharge cases[1]		*Low*		17%	19%	19%
		High		8%	9%	9%
2040						
Municipal and domestic	430	850	2,040	15,314	15,734	16,924
Industrial and mining	74,040	125,540	151,330	165,297	216,797	242,587
2040 Total	74,470	126,390	153,370	180,611	232,531	259,511
2040 total requirements as percentages of high and low recharge cases[1]		*Low*		24%	31%	34%
		High		11%	14%	16%
2060						
Municipal and domestic	720	1,490	3,660	15,604	16,374	18,544
Industrial and mining	148,470	281,100	355,750	239,727	372,357	447,007
2060 Total	149,190	282,590	359,410	255,331	388,731	465,551
2060 total requirements as percentages of high and low recharge cases[1]		*Low*		34%	51%	62%
		High		15%	24%	28%

[1]**Recharge range (sedimentary aquifers) (Table 8-2b)**
Low – 775,458 ac-ft/yr
High – 1,650,691 ac-ft/yr

[2]**Current annual groundwater withdrawals (Table 8-2c)**
Municipal and domestic (high-end) **14,884** ac-ft
Industrial and mining **91,257** ac-ft

As discussed above, the better case for such analyses uses recharge to only the sedimentary aquifers (**Table 8-2d**, far-right column). Similarly, Table **8-2e** (far-right column) summarizes various groundwater (high-estimate) use statistics as percentages of recharge to sedimentary aquifers.

According to these analyses, average recharge to the sedimentary aquifers in the WBRB (1,203,000 ac-ft – mean of high and low estimates, **Table 8-2d**) and consumptive use (1,270,000 ac-ft – **Table 8-2d**) are approximately equal; and total recharge to the WBRB, even the low estimate (3,025,000 ac-ft – **Table 8-2b**) far exceeds groundwater withdrawals (164,000 ac-ft) and consumptive use (46,000 ac-ft – high-end estimates, **Table 8-2c**). The estimates of total average annual groundwater use could be substantially higher, and the estimates of recharge substantially lower, without significantly changing the simple comparative results. In addition, most of total groundwater withdrawal is saline produced water from oil and gas operations that would not otherwise be generated as a groundwater resource, but only as a byproduct, and therefore should not be considered as a reduction of beneficially useable groundwater resources. While this analysis indicates that groundwater resources are underutilized overall in the WBRB, it does not take into account the highly location-specific nature of groundwater resource development. This issue is discussed further in **Chapter 9** in relation to future groundwater development in the WBRB.

It is also useful to evaluate future groundwater requirements relative to recharge. The Update Water Plan (MWH et al., 2010a) provides estimates of annual groundwater requirements above existing withdrawals for municipal and domestic uses and for industrial and mining uses in 2020, 2040, and 2060, for three demand scenarios (low, medium, high); these are presented in **Table 8-2f**. Future groundwater requirements for agricultural and recreational/environmental uses were

not estimated. The 2003 Water Plan (BRS, Inc et al., 2003) projected that almost all new water demand in the WBRB would be met with surface water. In contrast, the current 2010 Update Water Plan projects that approximately 43 percent of new water demand will be met with groundwater, primarily associated with industrial/mining production, and that the remaining 57 percent will be met with surface water used for agricultural development.

Future annual groundwater requirements for six cases (high and low recharge vs. low, medium, and high demand) for each of three progressive time-frames (2020, 2040, 2060) are calculated in **Table 8-2f** by adding the additional requirement estimates to the current annual withdrawals for municipal/domestic and industrial/mining uses.

By this analysis, future groundwater requirements as a percentage of recharge range from 8 to 19 percent in 2020, from 11 to 34 percent in 2040, and from 15 to 62 percent in 2060. Similarly to the evaluation of recharge vs. current groundwater withdrawals **(Table 8-2e)**, the corresponding analysis for future demand indicates that recharge will be adequate to maintain groundwater as an underutilized resource in the WBRB well into the future. And likewise, because the presence of groundwater resources that can actually be developed is location-specific, the potential for overutilization of groundwater resources is also location-specific.

The following sections discuss the uses that account for almost all the groundwater withdrawals estimated in the 2003 and 2010 Update Water Plans for the WBRB.

8.1.1 Irrigation

Irrigation use was estimated in the previous Available Groundwater Determination at 88.5 million gallons per day (MGD) (271.5 ac-ft/d) on the basis permitted yield from 138 irrigation wells (Lidstone and Associates, 2003). To estimate average annual withdrawal for **Table 8-2c** (41,540 ac-ft), the average daily rate of withdrawal was multiplied by the average number of days in the irrigation season (153, May 1 to September 30). Most irrigation use is permitted for croplands along streams where water is obtained at relatively shallow depth from Quaternary alluvial aquifers, to a lesser extent Tertiary bedrock aquifers, and along the basin margins primarily from highly productive Paleozoic aquifers. Irrigation is partially consumptive (plant growth and evapotranspiration), and was estimated at 34.4 percent of total withdrawals for irrigation (MWH et al., 2010b). Because it is unlikely that the entire permitted allotment of groundwater for irrigation is used during any year, this estimate is most likely overstated, perhaps significantly.

8.1.2 Livestock watering

Water requirements for livestock in the WBRB (6,370 ac-ft/yr) **(Table 8-2c)** was estimated in the Update Water Plan (MWH et al., 2010b) on a per-animal-unit basis (cattle, calves, dairy cows, horses, sheep, goats, pigs, llamas, mules, and donkeys) using stock-specific daily water requirements provided by the National Resources Conservation Service (NRCS) for the number of animals, by county, based on 2007 Census data provided by the US Department of Agriculture (USDA). It was assumed that essentially all the water requirement for livestock is consumptively used groundwater. Total agricultural withdrawals in **Table 8-2c** (47,910 ac-ft/yr) reflects both irrigation and livestock groundwater use.

8.1.3 Municipal/community public water systems

Community public water systems supply water year-round to essentially the same population (USPEA, 2009). The previous Water Plan (Lidstone and Associates, 2003) identified 58 municipal water systems, 36 of which utilized 4,344 to 9,819 acre-feet of groundwater per year (32% of total municipal withdrawals). In contrast, the current Update Water Plan (MWH et. al, 2010a) found that as of 2009 the USEPA Safe Drinking Water Information System (SDWIS) listed 60 active systems in the WBRB (USEPA, 2009). Appendix A in the Municipal and Domestic Water Use Profile – Technical Memorandum to the 2010 Update Plan (MWH et al., 2010b) includes summary lists of the SDWIS data for the WBRB, including statistics on surface water and groundwater withdrawals; and Table 1 of the Technical Memorandum includes a list of 39 systems that obtain at least some municipal supply from groundwater from at least 85 wells. The current Update Water Plan (MWH et al., 2010a) estimates average groundwater withdrawal of 5,700 acre-feet per year from these systems, based on a 2009 WWDC study of 42 systems for which detailed information was available (**Table 8-2c)**. In either case, municipal use constitutes a relatively small part of overall groundwater withdrawal in the WBRB **(Table 8-2c)**. Information on which aquifers are used for community public supplies is provided later in this chapter **(Section 8.3.5.1)**. The current Water Plan indicates that the WSEO has permitted 136 wells for municipal use in the WBRB, and estimates that overall consumptive use of municipal withdrawals (both surface water and groundwater) is 41 percent (MWH et al., 2010a).

8.1.4 Non-community public water systems

Domestic water withdrawals include non-community public water systems and rural domestic users. The USEPA (2009) classifies non-community public water systems as either transient or non-transient. Transient systems provide water at locations where most of the population varies continuously and that are open at least 60 days per year (e.g., gas stations, campgrounds). Non-transient systems regularly supply water to a stable population of at least 25 persons for at least six months per year (e.g., self-supplied facilities). The previous Water Plan (Lidstone and Associates, 2003) estimated 6.5 to 10.4 million gallons per day (MGD) (7,281 to 11,650 ac-ft/yr) total domestic water use in the WBRB, with 3.9 to 7.8 MGD

(4,369 to 8,737 ac-ft/yr) supplied by groundwater, including 2.57 MGD (2,879 ac-ft/yr) for non-municipal public systems. The previous WBRB Water Plan (BRS, Inc. et al., 2003) also identified 115 non-municipal public water systems that derive approximately 50 percent of their supply from groundwater sources, with most withdrawals occurring seasonally in Yellowstone National Park, and with use ranging from 150 to 300 gallons per capita per day (gpcpd) for a population estimated at 34,300.

The current Update Water Plan (MWH et al., 2010a) listed fewer water systems and assumed lower usage and population estimates than the 2003 water plan. The current Update Water Plan found that as of 2009 the USEPA Safe Drinking Water Information System (SDWIS) listed 98 non-community public water systems within the WBRB supplied from both groundwater and surface water sources (USEPA, 2009). Appendix A in the Municipal and Domestic Water Use Profile – Technical Memorandum to the 2010 Update Plan (MWH et al., 2010b) includes summary lists of SDWIS data for the WBRB, including statistics on groundwater withdrawals. On the basis of an assumed use of 75 gpcpd for a population of 18,400, total non-community system demands are estimated at 1568 acre-feet per year and total groundwater demand (at 50 percent of total withdrawals) at 784 acre-feet per year **(Table 8-2c)**. Similarly to estimates for municipal withdrawals, although there is a notable difference between the 2003 and 2010 estimates, by both estimates non-community public use constitutes a relatively small part of overall groundwater withdrawal **(Table 8-2c)**. Consistent with the assumption for municipal use (MWH et al., 2010b), overall consumptive use by non-community systems (both surface water and groundwater) is estimated at 41 percent.

8.1.5 Rural domestic

Rural domestic withdrawals are for household uses that are not supplied by municipal (community) or non-community water systems. Lidstone and Associates (2002b) estimated 6.5 to 10.4 MGD (7,281 to 11,650 ac-ft/yr) total rural domestic water use in the WBRB, with 3.9 to 7.8 MGD (4,369 to 8,737 ac-ft/yr) supplied by groundwater, including 2.57 MGD (2,879 ac-ft/yr) for non-municipal public systems. The rural domestic population was estimated at 26,002 people; and all rural domestic withdrawals were assumed to be supplied by individual wells in Quaternary, Wind River, Willwood, or Paleozoic aquifers. Most (83 percent) of the rural domestic water wells were found to be located in Fremont and Park counties.

According to the current Water Plan (MWH et al., 2010b), as of 2009, the WSEO had issued 13,638 permits for domestic use, of which 9,693 are permitted for domestic use only and 3,945 are permitted for either domestic-stock use or domestic-other use. **Table 9** in the Municipal and Domestic Water Use Profile – Technical Memorandum to the 2010 Update Plan (MWH et al., 2010b) summarizes how multiple-use domestic wells are permitted in the WBRB counties. Assuming that most rural domestic water use in the WBRB is supplied from groundwater, domestic use by county was estimated by subtracting the total population served by community water systems included in the USEPA-SDWIS database from the estimated total population for each county. Assuming a population serviced by domestic wells of 25,120 and rural domestic use ranging from 150 to 300 gpcpd (Lidstone and Associates, 2003), the estimated rural domestic groundwater use is estimated at 3.8 to 7.5 MGD (4,256 to 8,400 ac-ft/yr). Table 10 in the Domestic and Municipal Use Technical Memorandum (MWH et al., 2010b) summarizes domestic use calculations by county. Similarly to municipal and non-community public system withdrawals, although there is a notable difference between the 2003 and 2010 estimates, by both estimates rural domestic use constitutes a relatively small part of overall groundwater withdrawal in the WBRB **(Table 8-2c)**. Consistent with the assumption for municipal and non-community systems use (MWH et al., 2010b), overall consumptive use of rural domestic groundwater is estimated at 41 percent.

8.1.6 Recreation and environmental

Recreation and environmental groundwater uses were estimated to be 4.78 MGD and 4.15 MGD, respectively (10,000 ac-ft/yr total) (Lidstone and Associates, 2003). Uses include fish hatcheries, campgrounds, and private recreational facilities; accordingly, an insignificant fraction of this use is expected to be consumptive. If these estimates are based on permitted amounts, they may be overstated. The current Water Plan (MWH et al., 2010a) did not discuss recreational and environmental uses of groundwater.

8.1.7 Industrial and mining

Overall industrial and mining water withdrawal in the WBRB includes demand for general industrial uses and non-fuels and fuels mining operations. Most industrial and mining water withdrawal (surface water and groundwater) in the WBRB is as byproduct produced water (groundwater) from conventional oil and gas operations. General industrial groundwater use includes withdrawal from permitted wells associated with self-supplied industrial facilities and operations such as fabrication, processing, washing, and cooling. Groundwater use in non-fuels mining includes the extraction and milling (crushing, screening, washing, flotation) and other activities directly associated with producing metallic and industrial mineral ores, stone, sand, and gravel. Groundwater use in fuels mining includes the production of uranium, coal, coalbed natural gas (CBNG), and conventional oil and gas. Groundwater withdrawn for industrial and both non-fuels and coal mining operations may be of poor quality and is commonly reused for

general industrial purposes such as dust control (MWH et al., 2010a). Oil and gas produced water is generally discharged to the surface and re-injected for either enhanced oil recovery or permanent disposal (storage).

The previous Water Plan (BRS Engineering, 2003a) estimated total industrial and mining water use in the WBRB at 92,240 acre-feet per year on the basis of permitted yields from 1999 WSEO data, with most withdrawals from conventional oil and gas operations totaling 73,790 acre-feet per year. Manufacturing withdrawals were estimated at 15,710 acre-feet per year, and withdrawals for mining (primarily bentonite and gypsum) were estimated at 2,740 acre-feet per year. Most withdrawals for industrial and mining uses (70,883 ac-ft/yr) were assumed to be from groundwater sources (Lidstone and Associates, 2003). As discussed previously, groundwater use based on permitted yields generally overestimates actual withdrawals. On the basis of Wyoming Oil and Gas Conservation Commission records, Lidstone and Associates (2003) estimated that 120,925 acre-feet of groundwater were produced from oil and gas wells in 2000.

The current Water Plan for the WBRB (MWH et al., 2010a) updates the 2003 estimates of industrial and mining withdrawals and also estimates consumptive use within the WBRB on the basis of information from the U.S. Geological Survey National Water Use Information Program (NWUIP). The NWUIP works with local, state, and federal agencies to collect and compile water-use information at the county, state, and national levels. The 2010 Water Plan estimates total industrial and mining use in the WBRB at 91,908 acre-feet per year, 650 acre-feet of surface water and 91,257 acre-feet of groundwater. Estimated total industrial and mining consumptive groundwater use is 19,030 acre-feet per year (21percent of total withdrawal). The estimated 91,257 acre-feet total groundwater withdrawal **(Table 8-2c)** comprises 806 acre-feet of fresh water (224 general industrial and 582 mining) and 90,451 acre-feet of saline produced water from oil and gas production. Table 1 in the Industrial and Mining Water Use Technical Memorandum for the 2010 Update Plan (MWH et al., 2010b) summarizes total groundwater withdrawals by WBRB counties.

The NWUIP data include fresh and saline water withdrawn for self-supplied industrial and mining operations. MWH et al. (2010a) indicate that as of 2009 the WSEO had issued 347 permits for industrial operations and 28 permits for CBNG production in the WBRB. A list of these permits is provided in Appendix A in the Industrial and Mining Water Use Technical Memorandum for the 2010 Update Plan (MWH et al., 2010b). Water for industrial use supplied by municipal sources was included in estimates of municipal and domestic use. Oil and gas produced water is generally discharged to the surface and re-injected either for enhanced oil and gas recovery or for permanent disposal. NWUIP estimated total withdrawal by adding the volumes of all produced water injected and discharged within the WBRB. Records of produced water injection were obtained from the WOGCC. Records of produced water discharge were obtained from the Wyoming Department of Environmental Quality National Pollutant Discharge Elimination System (WYPDES) database.

NWUIP groundwater consumptive use estimates by type of industry or mining activity range from 10 to 90 percent of total withdrawal. On the basis of averages from the NWUIP data, MWH et al., (2010a) estimated total consumptive groundwater use for industrial and mining purposes at 19,030 acre-feet per year, approximately 21 percent of total fresh and saline withdrawal (91,257 ac-ft/yr). Consumptive use of fresh groundwater withdrawals for self-supplied industrial facilities was estimated at 39 acre-feet per year (MWH et al., 2010a). Consumptive use for mining was estimated at 191 acre-feet per year of fresh-water withdrawal and 18,880 acre-feet per year of saline withdrawal. On the basis of these amounts, **Table 8-2c** totals groundwater consumptive use at 19,110 acre-feet per year.

Most industrial and mining groundwater that is not consumptively used is either discharged to surface water or injected for enhanced oil and gas production or permanent disposal. This provides an alternate method of estimating industrial and mining consumptive groundwater use, by subtracting total produced water discharge (71,183 ac-ft/yr) from total groundwater withdrawal (91,257 ac-ft/yr) (MWH et al., 2010a). The difference is 20,074 acre-feet per year, giving a range of total industrial and mining consumptive groundwater use in the WBRB of 19,030 to 20,074 acre-feet per year (21 percent to 22 percent of total withdrawal). The average annual volume of produced water re-injected (964 ac-ft/yr) can be estimated by subtracting the amount discharged under WYPDES permits (71,183 ac-ft/yr) from non-consumptive withdrawals based on the NWUIP data (72,147 ac-ft/yr). Appendix B in the Industrial and Mining Water Use Technical Memorandum for the 2010 Update Plan (MWH et al., 2010b) provides a list of WYPDES surface water discharge permits in the WBRB.

Estimates of industrial and mining groundwater withdrawal in the 2003 and 2010 Water Plans are similar. This is somewhat surprising, as use in the 2003 Plan was based solely on WSEO permitted yields, which tend to overestimate actual withdrawal. In contrast, consumptive use estimated in the 2010 Updated Plan is significantly lower than the 2003 estimates, which were assumed to be 100 percent of permitted yield. **Table 8-2c** shows that industrial and mining withdrawals exceed all other uses for groundwater combined in the WBRB by a substantial amount [91,257 vs. 72,795 ac-ft/yr (high-end)].

Because produced water from oil and gas operations is a byproduct, probably would not be withdrawn for any other purpose, and makes up most groundwater withdrawal in the WBRB, when it is discharged to surface water it increases the overall surface water supply in the WBRB without depleting useable groundwater resources. Similarly, it can be argued that injecting produced water for enhanced oil and gas recovery or permanent disposal into aquifers generally too deep to be considered for groundwater development effectively removes water from the system and is, therefore, consumptive.

8.2 Information from hydrogeologic units studies

In addition to the information compiled from state and federal agencies on groundwater volumes withdrawn for the use categories presented above, information concerning groundwater use associated with specific hydrogeologic units was compiled from a variety sources for the **Chapter 7** discussion of hydrogeologic units in the WBRB. **Chapter 7** summarizes the physical, hydrogeologic, and chemical characteristics of the hydrogeologic units and the recharge, discharge, and groundwater circulation of the aquifers and aquifer systems in the WBRB. To the extent that data were available, the current uses and potential for development of the specific hydrogeologic units are summarized in **Appendix D**. Table 2 of the WWDC 2003 Available Ground Water Determination Technical Memorandum (Lidstone and Associates, 2003) provides similar tabulated aquifer-specific information. **Appendix B** is a chronological summary of the locations, aquifers, focus, results, and status of groundwater development studies in the WBRB that have been sponsored by the WWDC since 1982. Many of these studies were used in compiling the information presented in **Chapter 7**; thus, the data concerning current groundwater uses is generally summarized in **Appendix D**.

8.3 Groundwater permits information

Groundwater development proceeds primarily by installing water supply wells and, to a much lesser degree, by developing natural springs. The WSEO issues permits to appropriate groundwater throughout Wyoming. The Joint Tribal Water Engineer (TWE) of the Wind River Indian Reservation issues some permits within the Reservation. The Montana Bureau of Mines and Geology (MBMG) issues permits to appropriate groundwater in Montana. For this study the WSGS acquired groundwater permit data from all three agencies and provided copies of the WSEO data to MWH for their use in the 2010 Update Water Plan (MWH et al., 2010a) and associated Technical Memoranda. The WSEO provided information on approximately **19,508** groundwater permits through June 2009, including **682** permits (through 1985) that WSEO obtained from the TWE. The MBMG issued **45** permits through August 2009 for appropriating groundwater in the northernmost WBRB. The WSEO groundwater-permit database for the WBRB includes information on **620** springs. Information on specific WSEO groundwater permits for the Wyoming WBRB (and throughout Wyoming) can be accessed through the WSEO on-line water rights database using various search parameters (e.g., permit number, location, applicant, use) at

http://seo.state.wy.us/wrdb/PS_WellLocation.aspx

Groundwater permit data for the Wind River Indian Reservation used in this study include information only through 1985, acquired by WSEO from the Reservation pursuant to a lawsuit. There are also many permits within the Reservation that have been issued directly by the WSEO, both before and after 1985, that were not included in the Reservation data. The TWE has been the permitting agency for the Reservation since 1984 for yields to 25 gpm, and the WSEO issues permits for yields greater than 25 gpm (pers.comm.; Baptiste Weed, TWE, 2011).

There are probably permits for a variety of uses on the Reservation for which there are no WSEO records and that were not available for this study. The TWE is currently compiling a comprehensive database for all groundwater permits on the Reservation. Additional or unique information

Table 8-3. WSEO groundwater permits in the Wyoming WBRB database by permit status.

Permit status	*All permits through 06/2009*	*New permits 2000–06/2009*
1 - Fully adjudicated	6531	16
2 - Complete	5731	1945
3 - Unadjudicated	4	4
4 - Incomplete	991	602
5 - Abandoned	249	1
6 - Expired	36	1
7 - Cancelled	3739	388
8 - undefined	2227	1734
Total permits	**19,508**	**4,691**
Probable wells drilled	**12,515 – 14,742 (64.2 – 75.6%)**	**1,966 – 3,700 (41.9 – 78.9%)**
Probable total existing wells	**12,266 – 14,493 (62.9 – 74.3%)**	**1,965 – 3,699 (41.9 – 78.9 %)**

on specific areas or groundwater permits on the Wind River Indian Reservation might be obtained from the Office of the Tribal Water Engineer at

15 N. Fork Road
P.O. Box 217
Fort Washakie, WY 82514
(307) 332-6464

Information on specific groundwater permits from the MBMG for the Montana WBRB can be accessed at

Montana Bureau of Mines and Geology
Natural Resource Building
1505 West Park Street
Butte, MT 59701-8932

or

Montana Bureau of Mines and Geology
Poly Building
1300 North 27th Street
Billings, MT 59101-0245

or *http://www.mbmg.mtech.edu*

Table 8-4. WSEO groundwater permits in the Wyoming WBRB database by depth range.

All permits				
Depth range (feet)	***Permits***	***Percentage***	***Cumulative permits***	***Cumulative percentage***
0–50	5,344	41.08%	5,344	41.08%
50–100	2,971	22.84	8,315	63.92
100–500	3,863	29.69	12,178	93.61
500–1,000	522	4.01	12,700	97.62
> 1,000	309	2.38	13,009	100
Permits with depth information	**13,009**			
Permits with no depth information	**5,672**	**30.36%** (of total)	**18,681**	
Total permits	**18,681**			
New permits since 2000				
0–50	1,067	49.60%	1,067	49.60%
50–100	396	18.41	1,463	68.01
100–500	557	25.89	2,020	93.91
500–1,000	87	4.04	2,107	97.95
> 1,000	44	2.05	2,151	100
Permits with depth information	**2,151**			
Permits with no depth information	**2,538**	**54.13%** (of total)	**4,689**	
Total permits	**4,689**			

Table 8-5. WSEO groundwater permits in the Wyoming WBRB database by yield range.

All permits				
Yield range (gpm)	***Permits***	***Percentage***	***Cumulative permits***	***Cumulative percentage***
0–25	18,147	93.33%	18,147	93.33%
25–100	675	3.47	18,822	96.80
100–500	413	2.12	19,235	98.93
500–1,000	117	0.60	19,352	99.53
> 1,000	92	0.47	19,444	100
Total	**19,444**			
New permits since 2000				
0–25	4,449	94.76%	4,449	94.76%
25–100	140	2.98	4,589	97.74
100–500	79	1.68	4,668	99.42
500–1,000	17	0.36	4,685	99.79
> 1,000	10	0.21	4,695	100
Total	**4,695**			

Table 8-6. WSEO groundwater permits in the Wyoming WBRB database by intended use.

Permit type	*WSEO code*	*Total number of permits*	*New since 2000*	*Total permitted yield (gpm)*
Municipal	MUN	130	13	60,730
Domestic	DOM	12,876	3,114	284,644
Industrial	IND	341	12	68,167
Coalbed natural gas (CBNG)	CBM	27	22	977
Irrigation	IRR	458	95	210,077
Stock	STK	5,796	1,440	210,966
Miscellaneous	MIS	1,754	462	153,128
Monitor	MON	1,913	476	1,341
Test	TST	97	89	525
Other	--	50	2	1717
Total		**23,442**	**5,725**	**992,272**

The maps in **Chapter 8** of permit locations by use illustrate the distribution of permit data in the WBRB. Groundwater-permit data is tabulated in this section to summarize the number of permits by

- permit status
- depth range
- yield range
- user (Wyoming, Wind River Indian Reservation, Montana)
- municipal use, including producing hydrogeologic unit
- WDEQ Source Water Assessment Program (SWAP) program

In addition, the permit data are tabulated (by depth vs. yield) on maps depicting well (and spring) locations on **Plates IV and XI, and Figures 8-1 through 8-10**. The permit data are also included in various tables and maps in the 2010 Water Plan (MWH et al., 2010a) and associated Technical Memoranda. In general, the WSEO data are tabulated and mapped in this study for all permits through June 2009 and for permits from 2000 through June 2009 to illustrate development over the last decade.

Table 8-7. WSEO groundwater permits in the Wind River Indian Reservation WBRB database by intended use.

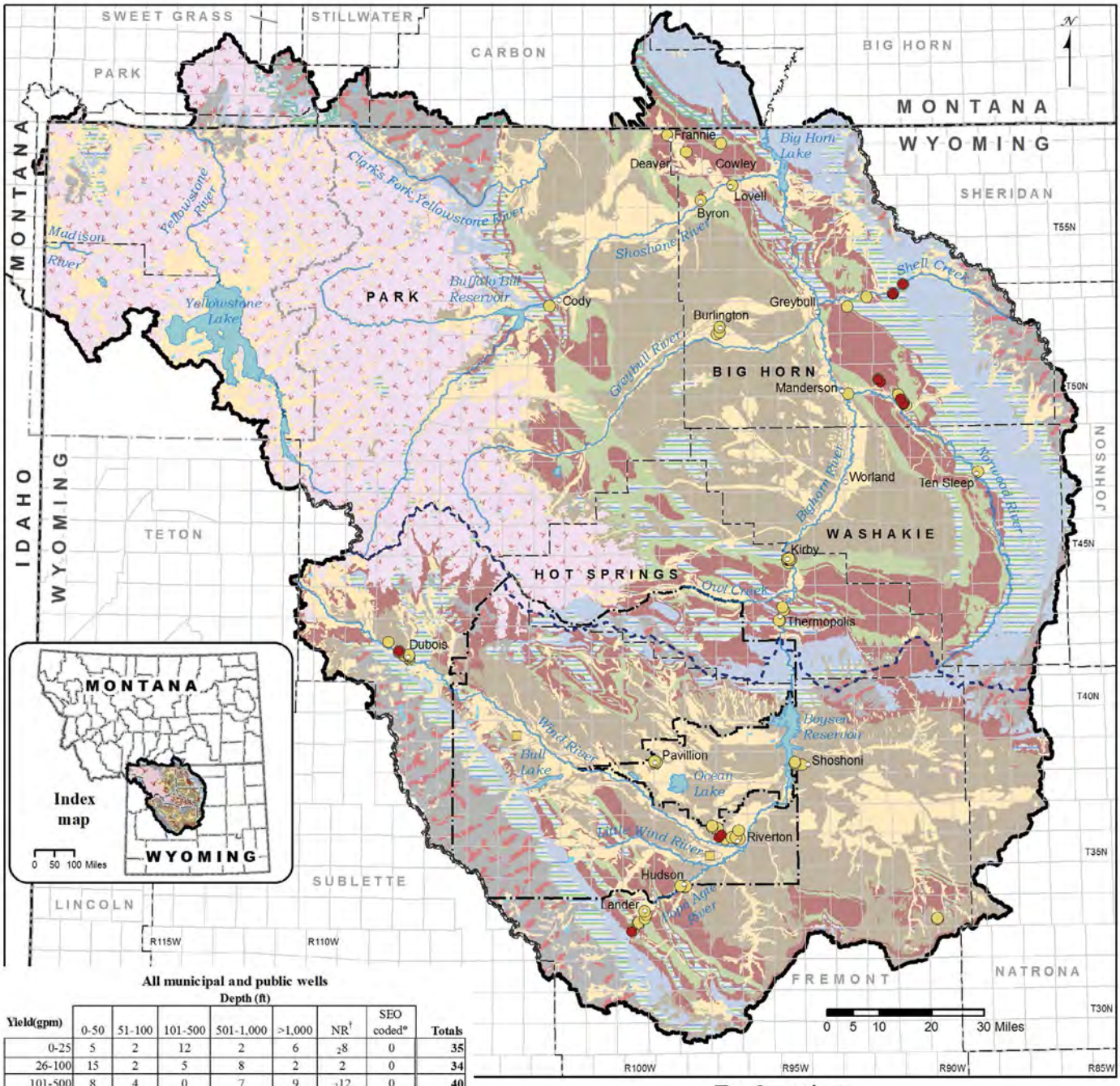
Permit type	*Code*	*Number*	*New since 2000*	*Total permitted yield (gpm)*
Public	PUB	3	0	184
Domestic	DOM	627	0	8,383
Mineral	MIN	8	0	1,101
Commercial	COM	2	0	501
Irrigation	IRR	1	0	50
Stock	STK	40	0	995
Miscellaneous	MIS	1	0	100
Other	--	2	0	0
Total		**684**	**0**	**11,314**

8.3.1 Groundwater permits by permit status

Table 8-3 shows the number of permits by the following eight permit-status categories. **Table 8-3** does not include permits from the MBMG or the TWE.

1. **Fully Adjudicated** – The well has been drilled and inspected, and a certificate of appropriation issued.
2. **Complete** – A notice of completion of the well has been received.
3. **Unadjudicated** – The well has not yet been inspected but may have been drilled.
4. **Incomplete** – Notice of completion of the well has not been received.
5. **Abandoned** – Notice that the well has been physically abandoned has been received.
6. **Expired** – The permit to appropriate groundwater has expired, generally because a notice that the well has been completed has not been received within the time period specified in the original permit or extension.
7. **Cancelled** – The permit has been cancelled, generally by the original permit applicant but perhaps for other reasons.
8. **Undefined** – The permit shows no designated status.

Status categories 1, 2, 3, and 5 indicate that permitted wells have been or probably have been drilled; categories 4, 6, and 7 indicate that the wells probably were not completed. For several permits (category 8), status is not included in the database. While **Table 8-3** summarizes only the number of permits issued to develop and use groundwater, permit status



All municipal and public wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	5	2	12	2	6	₂8	0	35
26-100	15	2	5	8	2	2	0	34
101-500	8	4	0	7	9	₂12	0	40
501-1,000	0	0	0	1	3	5	0	9
>1,000	1	0	0	0	6	6	0	13
SEO coded*	0	0	0	0	1	0	1	2
Totals	**29**	**8**	**17**	**18**	**27**	**33**	**1**	**133**

New municipal and public wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	0	1	0	0	4	0	0	5
26-100	0	0	0	0	1	0	0	1
101-500	0	0	0	0	0	2	0	2
501-1,000	0	0	0	0	0	0	0	0
>1,000	0	0	0	0	2	3	0	5
SEO coded*	0	0	0	0	0	0	0	0
Totals	**0**	**1**	**0**	**0**	**7**	**5**	**0**	**13**

†NR = Not recorded
*See Section 8.3.5
₂Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all of those wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Municipal well - since 2000
- Municipal well - before 2000
- Tribal public well - before 2000

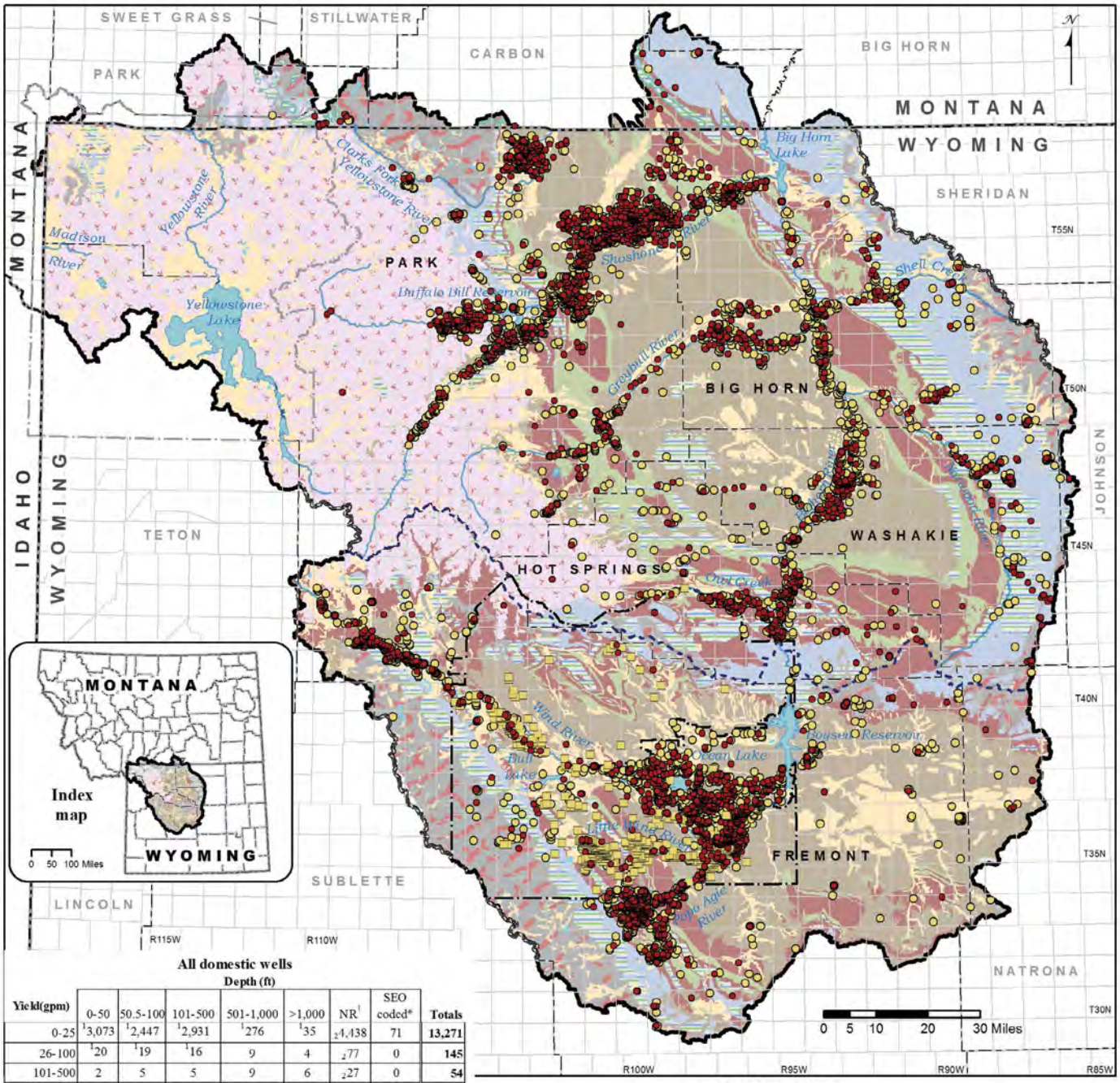
Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

WSGS 2011
Projection: NAD 1983
UTM Zone 12N

Data Source:
Wyoming State Engineer's Office

Figure 8-1. Permitted municipal wells, Wind/Bighorn River Basin.



All domestic wells

Yield(gpm)	Depth (ft) 0-50	50.5-100	101-500	501-1,000	>1,000	NR[†]	SEO coded*	Totals
0-25	[1]3,073	[1]2,447	[1]2,931	[1]276	[1]35	[2]4,438	71	**13,271**
26-100	[1]20	[1]19	[1]16	9	4	[2]77	0	**145**
101-500	2	5	5	9	6	[2]27	0	**54**
501-1,000	1	0	0	0	1	11	0	**13**
>1,000	1	0	1	0	2	11	0	**15**
SEO coded*	10	8	11	1	2	1	10	**43**
Totals	**3,107**	**2,479**	**2,964**	**295**	**50**	**4,565**	**81**	**13,541**

New domestic wells, since 2000

Yield(gpm)	Depth (ft) 0-50	50.5-100	101-500	501-1,000	>1,000	NR[†]	SEO coded*	Totals
0-25	[1]512	[1]327	[1]436	[1]57	[1]9	1764	2	**3,107**
26-100	[1]2	[1]4	[1]2	0	0	13	0	**21**
101-500	0	1	0	3	2	7	0	**13**
501-1,000	0	0	0	0	0	3	0	**3**
>1,000	0	0	0	0	0	1	0	**1**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**514**	**332**	**438**	**60**	**11**	**1,788**	**2**	**3,145**

[†]NR = Not recorded
*See Section 8.3.5
[1]Data includes Montana wells.
[2]Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all of those wells are placed in the [†]NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Domestic well - since 2000
- Domestic well - before 2000
- Tribal domestic well - before 2000

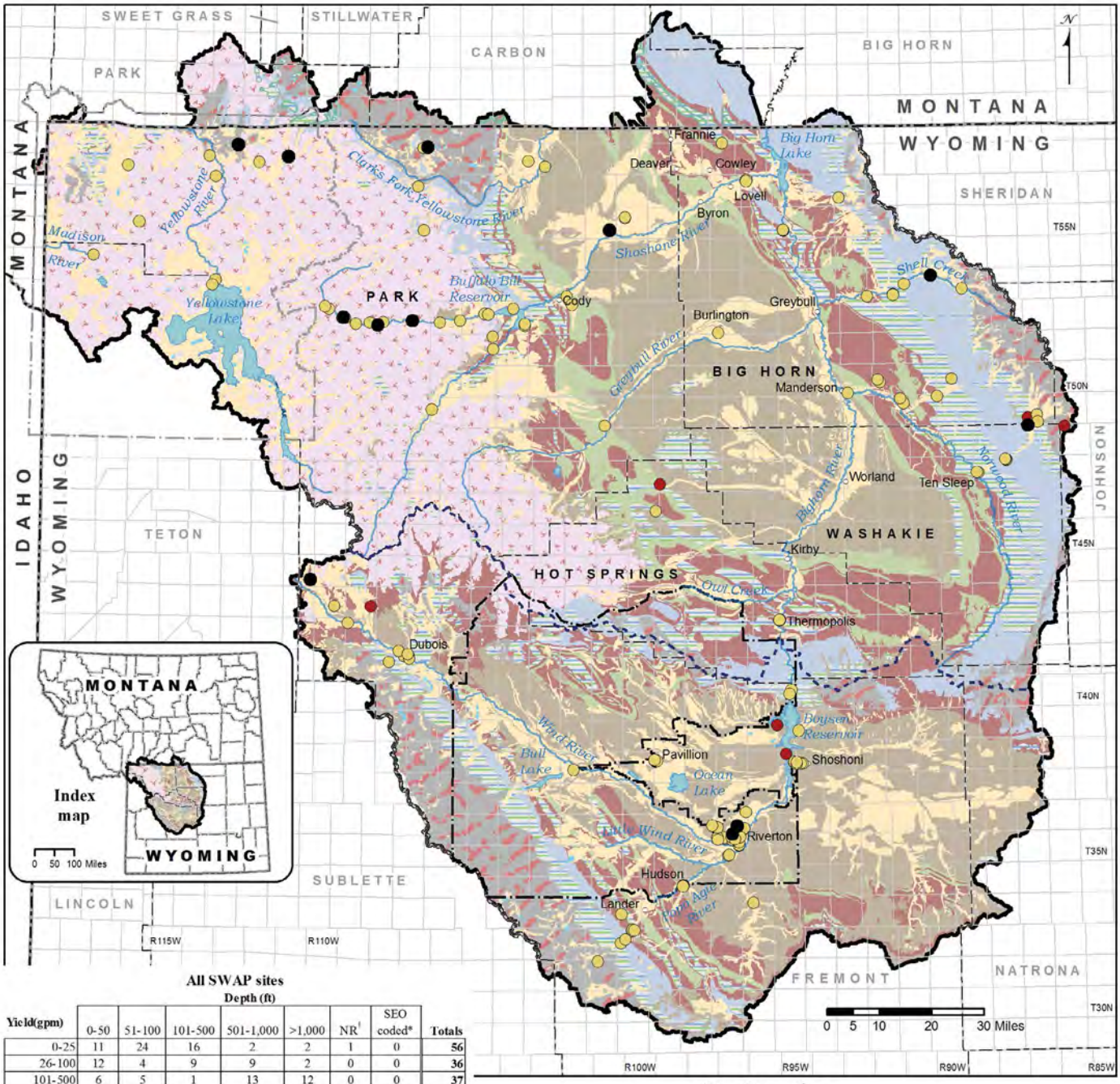
Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

WSGS 2011
Projection: NAD 1983
UTM Zone 12N

Data Sources:
Montana Bureau of Mines and Geology
Wind River Indian Reservation
Wyoming State Engineer's Office

Figure 8-2. Permitted domestic wells, Wind/Bighorn River Basin.



All SWAP sites

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	11	24	16	2	2	1	0	56
26-100	12	4	9	9	2	0	0	36
101-500	6	5	1	13	12	0	0	37
501-1,000	1	0	0	1	3	0	0	5
>1,000	0	0	0	0	3	0	0	3
NR†	0	0	0	1	0	33	0	34
SEO coded*	0	0	0	0	0	0	0	0
Totals	**30**	**33**	**26**	**26**	**22**	**34**	**0**	**171**

New SWAP sites, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	0	0	1	1	1	0	0	3
26-100	0	0	0	0	0	0	0	0
101-500	0	0	0	0	0	0	0	0
501-1,000	0	0	0	0	0	0	0	0
>1,000	0	0	0	0	0	0	0	0
NR†	0	0	0	1	0	2	0	3
SEO coded*	0	0	0	0	0	0	0	0
Totals	**0**	**0**	**1**	**2**	**1**	**2**	**0**	**6**

†NR = Not recorded
*See Section 8.3.5

Explanation

(See Figure 3-1 for explanation of additional symbols)

River
Lake
ice
SWAP site - since 2000
SWAP site - before 2000
SWAP site - date unknown

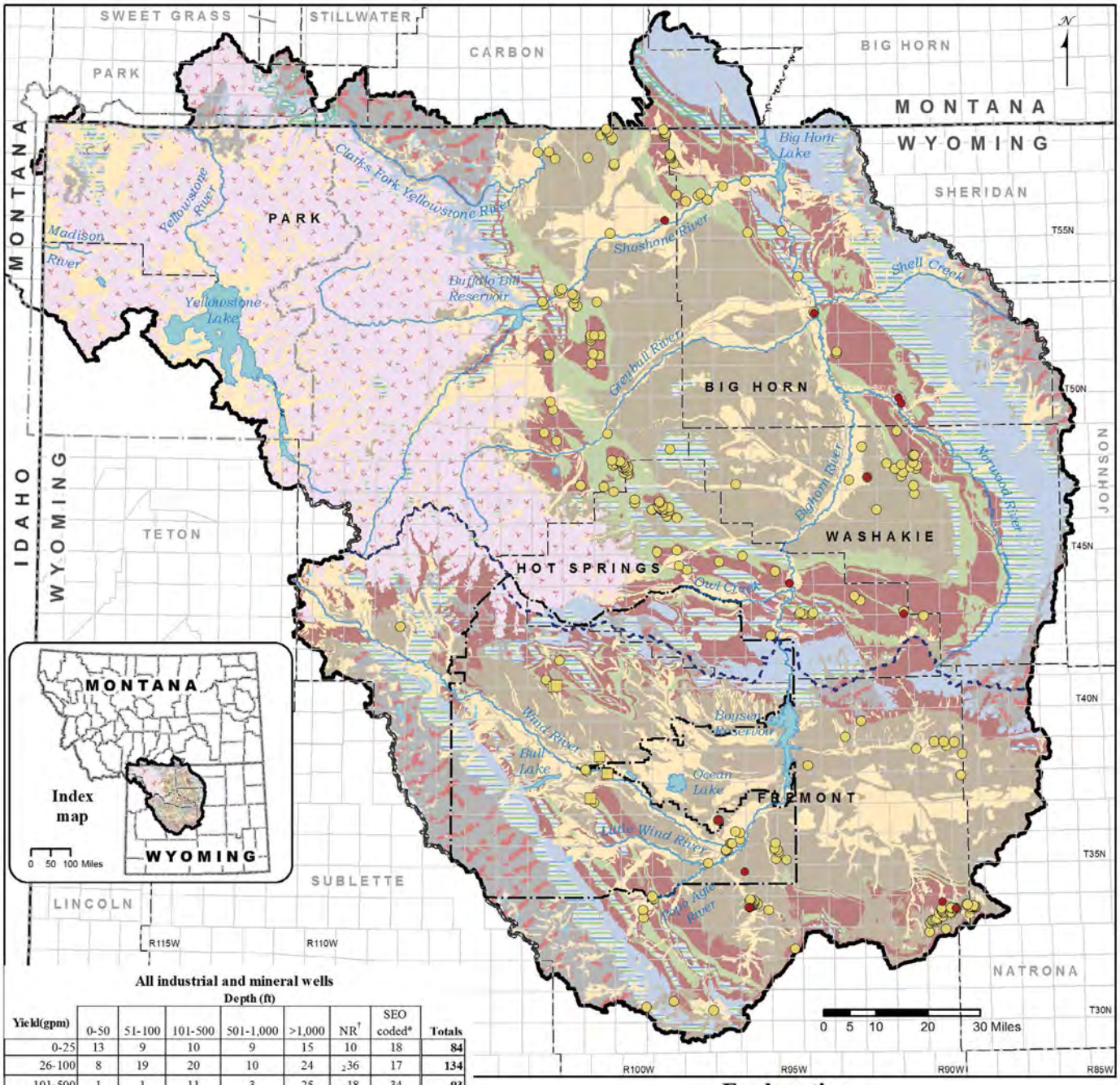
Hydrogeologic Units

Quaternary aquifers
Absaroka - Yellowstone volcanics
Tertiary aquifers
Mesozoic aquifers
Paleozoic aquifers
Undefined Tertiary, Mesozoic, and Paleozoic units
Precambrian aquifers
Confining units

WSGS 2011
Projection: NAD 1983
UTM Zone 12N

Data Sources:
Wyoming Department of Environmental Quality
Wyoming State Engineer's Office

Figure 8-3. Wyoming Department of Environmental Quality (WDEQ) Source Water Assessment Program (SWAP) sites, Wind/Bighorn River Basin.



All industrial and mineral wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	13	9	10	9	15	10	18	**84**
26-100	8	19	20	10	24	2 36	17	**134**
101-500	1	1	11	3	25	2 18	34	**93**
501-1,000	1	0	1	0	4	4	9	**19**
>1,000	1	0	0	0	0	3	10	**14**
SEO coded*	0	0	0	0	1	2	2	**5**
Totals	**24**	**29**	**42**	**22**	**69**	**73**	**90**	**349**

New industrial and mineral wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	1	1	0	0	0	1	0	**3**
26-100	0	0	0	0	0	2	0	**2**
101-500	0	0	0	0	0	1	0	**1**
501-1,000	1	0	0	1	2	2	0	**6**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**2**	**1**	**0**	**1**	**2**	**6**	**0**	**12**

†NR = Not recorded
*See Section 8.3.5
2Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all of those wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Industrial well - since 2000
- Industrial well - before 2000
- Tribal mineral well - before 2000

Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

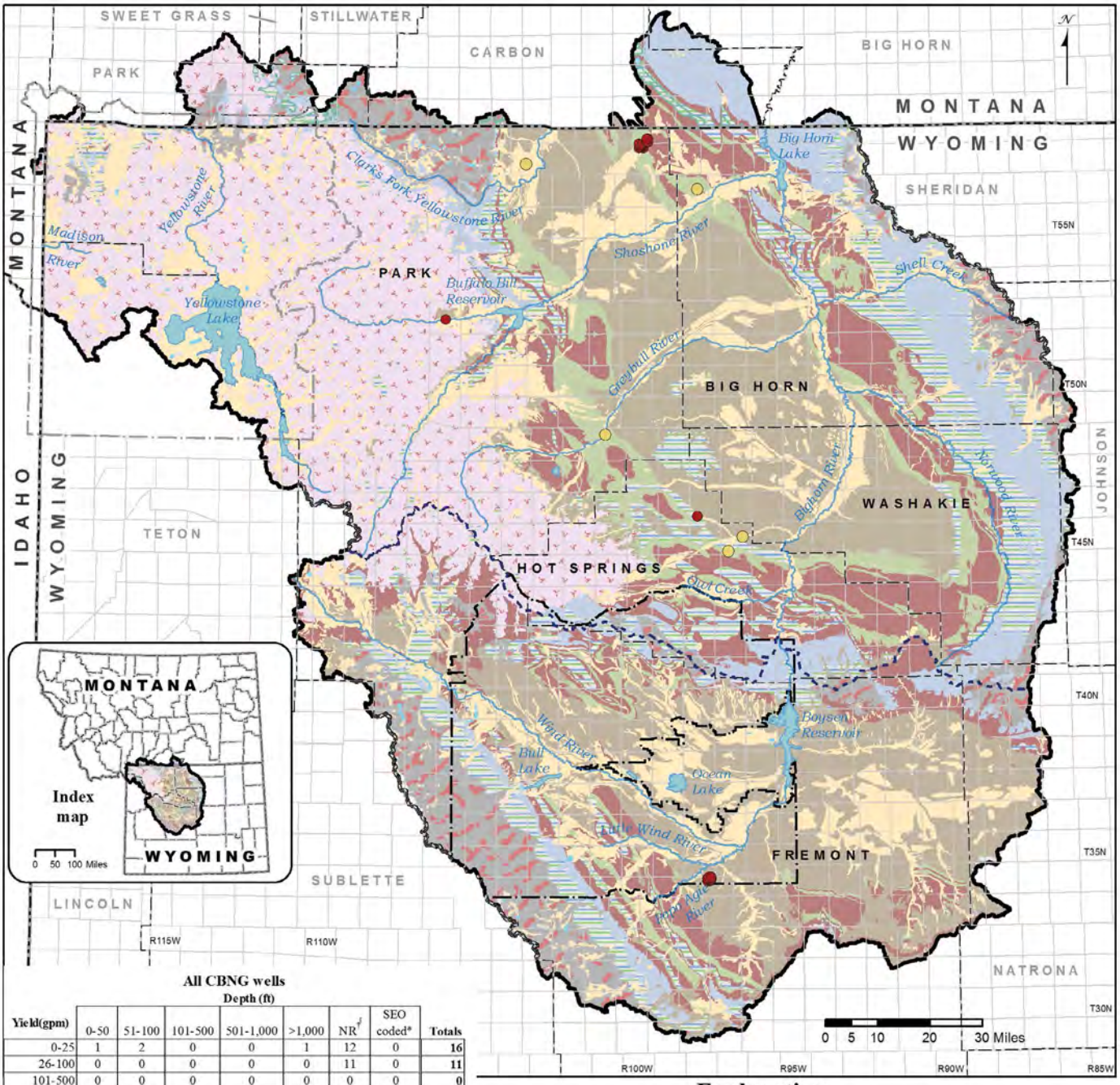
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Wind River Indian Reservation
Wyoming State Engineer's Office

Figure 8-4. Permitted industrial and mineral wells, Wind/Bighorn River Basin.



All CBNG wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	1	2	0	0	1	12	0	**16**
26-100	0	0	0	0	0	11	0	**11**
101-500	0	0	0	0	0	0	0	**0**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**1**	**2**	**0**	**0**	**1**	**23**	**0**	**27**

New CBNG wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	0	0	0	0	0	12	0	**12**
26-100	0	0	0	0	0	10	0	**10**
101-500	0	0	0	0	0	0	0	**0**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**0**	**0**	**0**	**0**	**0**	**22**	**0**	**22**

†NR = Not recorded
*See Section 8.3.5

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- CBNG well - since 2000
- CBNG well - before 2000

Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

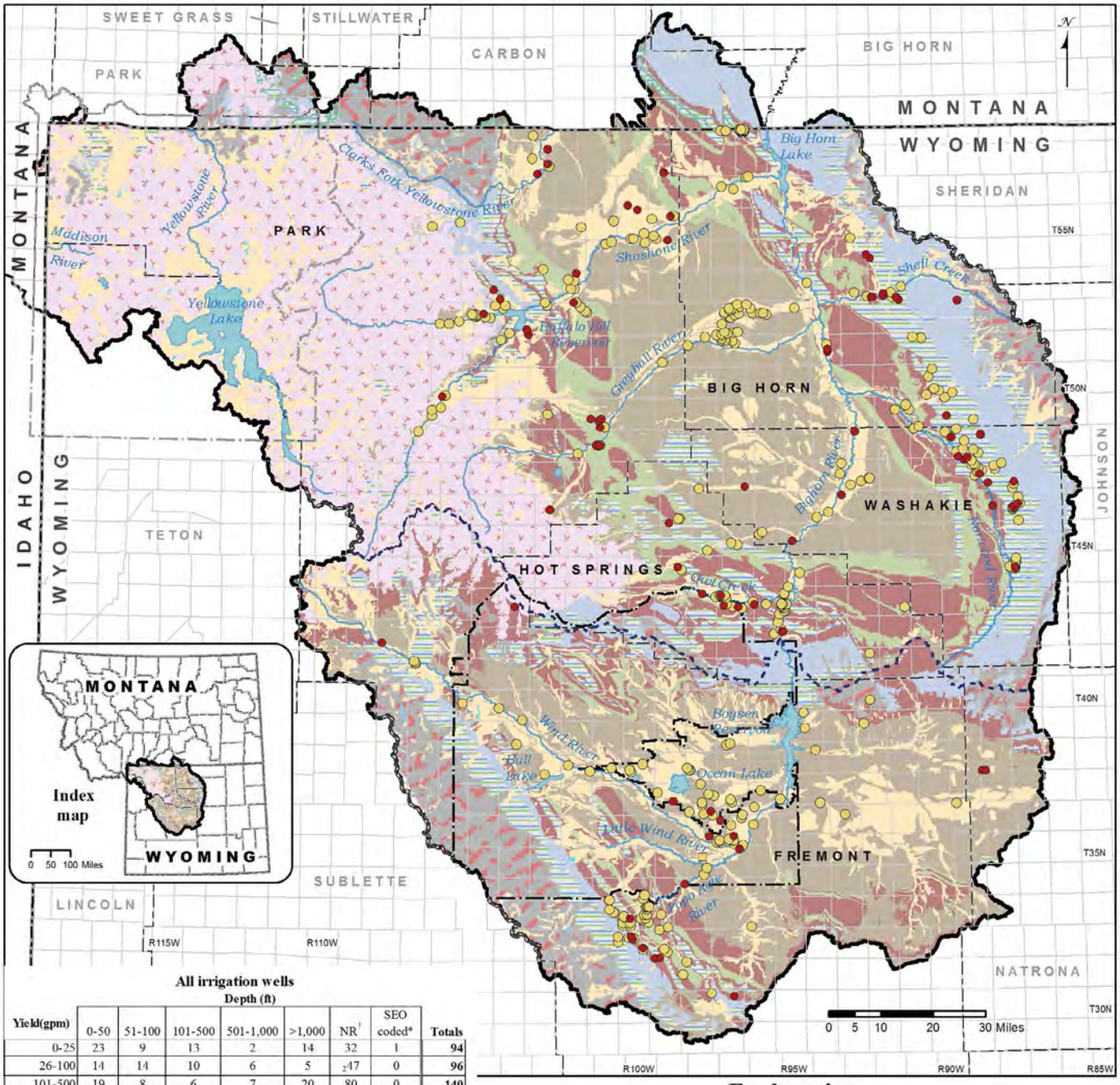
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Wyoming State Engineer's Office

Figure 8-5. Permitted coalbed natural gas (CBNG) wells, Wind/Bighorn River Basin.



All irrigation wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	23	9	13	2	14	32	1	**94**
26-100	14	14	10	6	5	‡47	0	**96**
101-500	19	8	6	7	20	80	0	**140**
501-1,000	17	1	5	0	9	34	1	**67**
>1,000	4	0	1	0	12	37	0	**54**
SEO coded*	3	1	0	0	1	3	0	**8**
Totals	**80**	**33**	**35**	**15**	**61**	**233**	**2**	**459**

New irrigation wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	6	1	2	1	3	13	0	**26**
26-100	5	2	1	0	0	16	0	**24**
101-500	2	1	1	3	6	22	0	**35**
501-1,000	0	0	0	0	0	5	0	**5**
>1,000	1	0	0	0	0	4	0	**5**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**14**	**4**	**4**	**4**	**9**	**60**	**0**	**95**

†NR = Not recorded
*See Section 8.3.5
‡Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all of those wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Irrigation well - since 2000
- Irrigation well - before 2000
- Tribal irrigation well - before 2000

Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

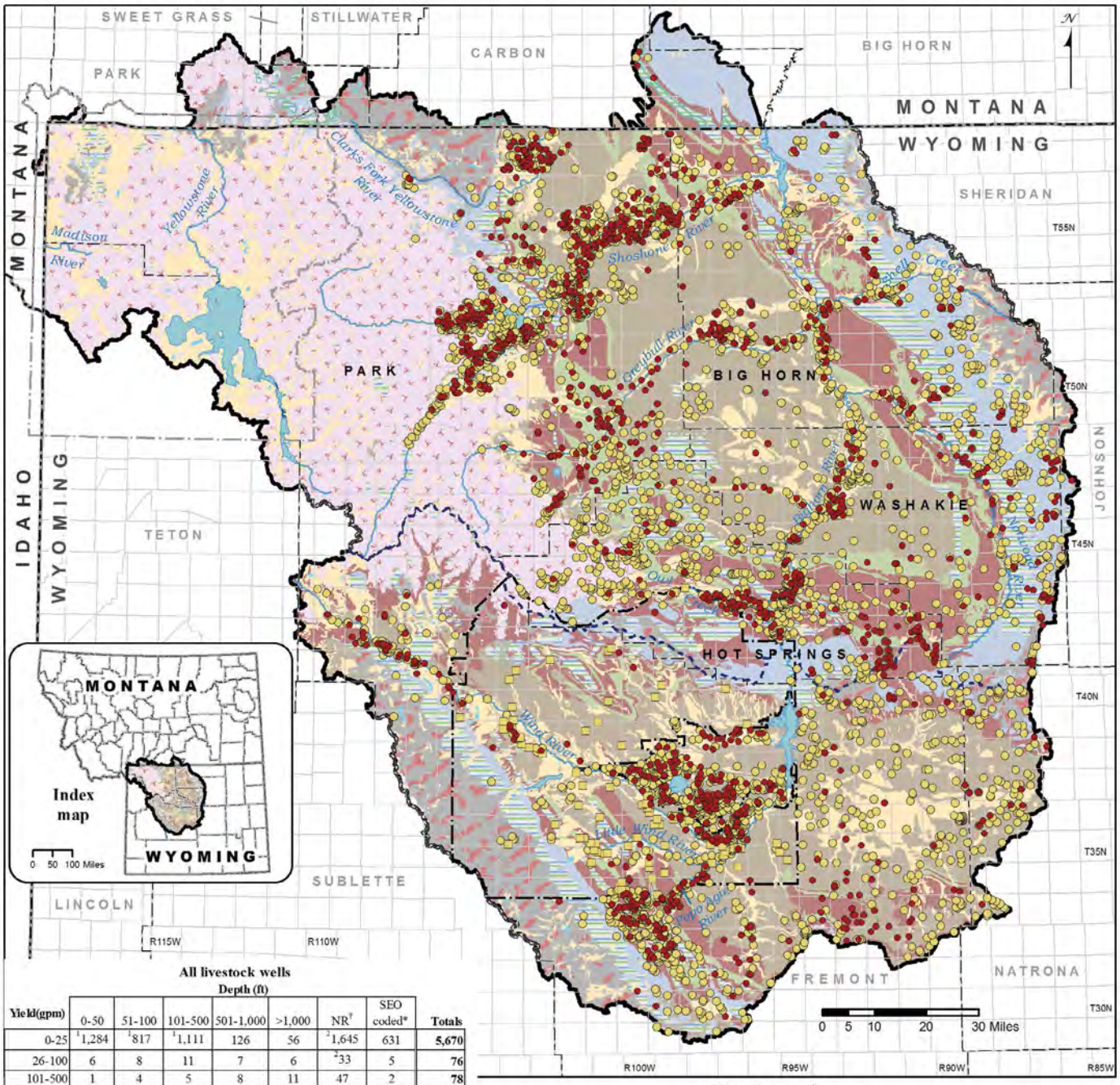
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Wind River Indian Reservation
Wyoming State Engineer's Office

Figure 8-6. Permitted irrigation wells, Wind/Bighorn River Basin.



All livestock wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	[1]1,284	[1]817	[1]1,111	126	56	[2]1,645	631	**5,670**
26-100	6	8	11	7	6	[2]33	5	**76**
101-500	1	4	5	8	11	47	2	**78**
501-1,000	0	1	1	0	5	16	0	**23**
>1,000	3	0	1	0	6	21	0	**31**
SEO coded*	6	4	3	1	1	1	2	**18**
Totals	**1,300**	**834**	**1,132**	**142**	**85**	**1,763**	**640**	**5,896**

New livestock wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	286	[1]116	[1]189	21	10	787	0	**1,409**
26-100	1	0	0	0	0	11	0	**12**
101-500	1	0	0	3	0	15	0	**19**
501-1,000	0	0	0	0	0	1	0	**1**
>1,000	0	0	0	0	0	3	0	**3**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**288**	**116**	**189**	**24**	**10**	**817**	**0**	**1,444**

†NR = Not recorded
*Wells for which a definite depth or yield is not assigned. See Section 8.3.5 for codes.
[1]Data includes Montana wells.
[2]Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all reservation wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

River
Lake
ice
Stock well - since 2000
Stock well - before 2000
Tribal stock well - before 2000

Hydrogeologic Units

Quaternary aquifers
Absaroka - Yellowstone volcanics
Tertiary aquifers
Mesozoic aquifers
Paleozoic aquifers
Undefined Tertiary, Mesozoic, and Paleozoic units
Precambrian aquifers
Confining units

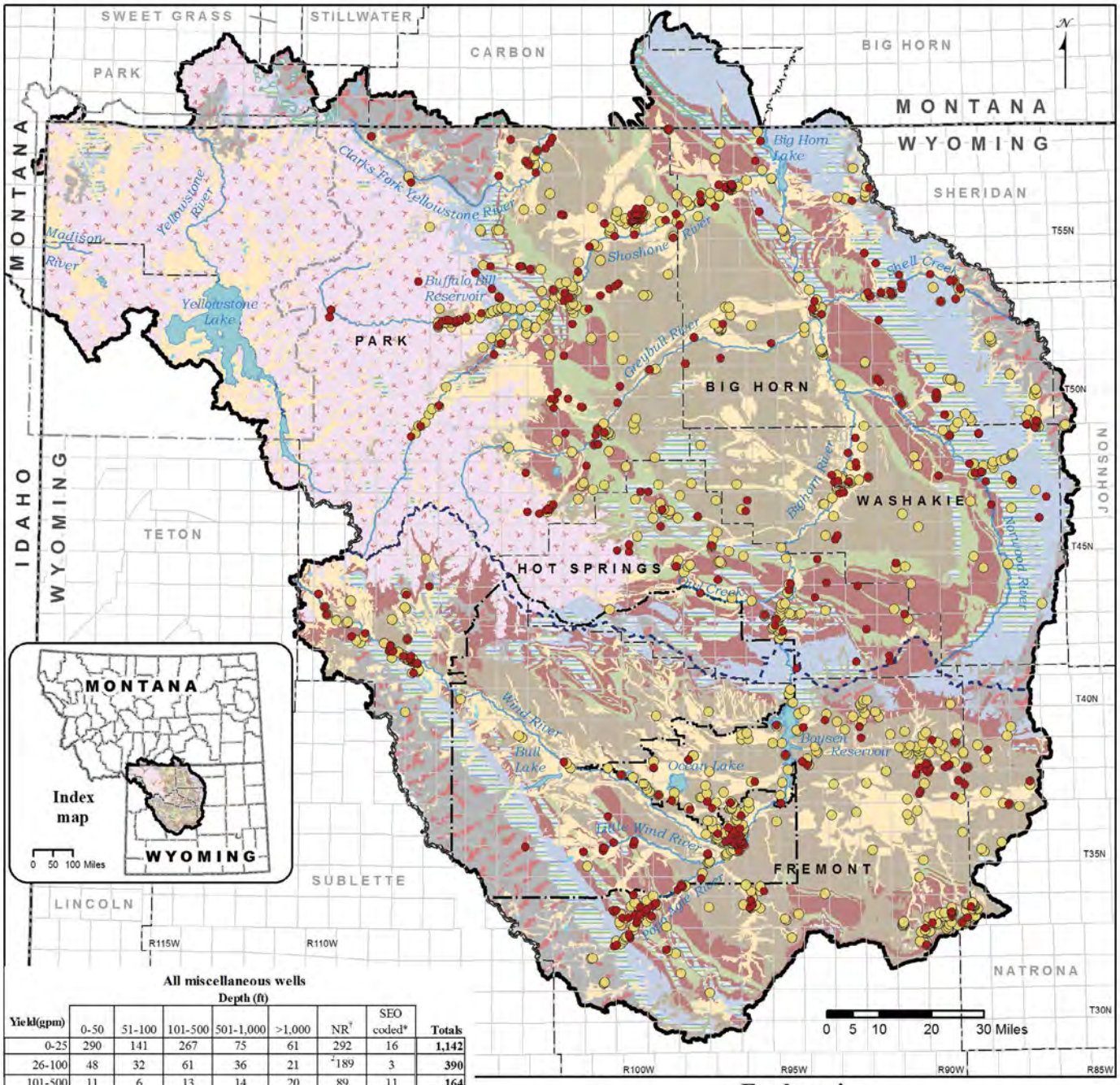
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Montana Bureau of Mines and Geology
Wind River Indian Reservation
Wyoming State Engineer's Office

Figure 8-7. Permitted livestock wells, Wind/Bighorn River Basin.



All miscellaneous wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	290	141	267	75	61	292	16	**1,142**
26-100	48	32	61	36	21	‡189	3	**390**
101-500	11	6	13	14	20	89	11	**164**
501-1,000	7	0	2	4	5	8	3	**29**
>1,000	6	0	4	0	3	8	4	**25**
SEO coded*	0	0	3	1	1	0	0	**5**
Totals	**362**	**179**	**350**	**130**	**111**	**586**	**37**	**1,755**

New miscellaneous wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	49	18	41	12	12	154	0	**286**
26-100	8	5	4	3	2	89	0	**111**
101-500	3	2	1	5	6	32	0	**49**
501-1,000	5	0	0	1	0	3	0	**9**
>1,000	1	0	0	0	2	4	0	**7**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**66**	**25**	**46**	**21**	**22**	**282**	**0**	**462**

†NR = Not recorded
*Wells for which a definite depth or yield is not assigned. See Section 8.3.5 for codes.
‡Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all reservation wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Miscellaneous well - since 2000
- Miscellaneous well - before 2000
- Tribal miscellaneous well - before 2000

Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

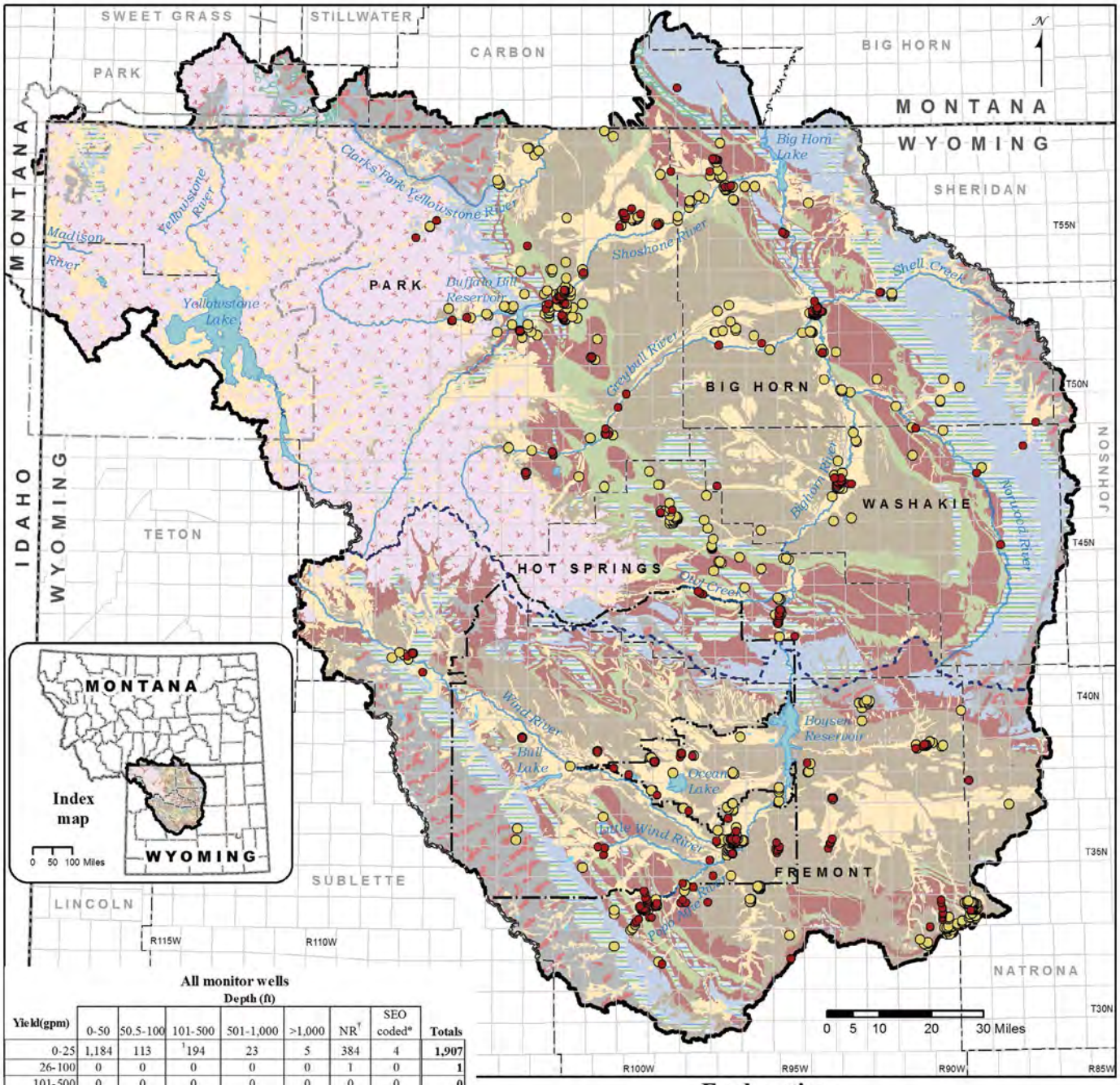
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Wind River Indian Reservation
Wyoming State Engineer's Office

Figure 8-8. Permitted miscellaneous wells, Wind/Bighorn River Basin.



All monitor wells

Yield(gpm)	Depth (ft) 0-50	50.5-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	1,184	113	‡194	23	5	384	4	**1,907**
26-100	0	0	0	0	0	1	0	**1**
101-500	0	0	0	0	0	0	0	**0**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	1	0	**1**
SEO coded*	0	1	2	2	0	0	0	**5**
Totals	**1,184**	**114**	**196**	**25**	**5**	**386**	**4**	**1,914**

New monitor wells, since 2000

Yield(gpm)	Depth (ft) 0-50	50.5-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	331	26	‡19	0	1	100	0	**477**
26-100	0	0	0	0	0	0	0	**0**
101-500	0	0	0	0	0	0	0	**0**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**331**	**26**	**19**	**0**	**1**	**100**	**0**	**477**

†NR = Not recorded
*See Section 8.3.5
‡Data includes Montana wells.

Explanation

(See Figure 3-1 for explanation of additional symbols)

- River
- Lake
- ice
- Monitor well - since 2000
- Monitor well - before 2000

Hydrogeologic Units

- Quaternary aquifers
- Absaroka - Yellowstone volcanics
- Tertiary aquifers
- Mesozoic aquifers
- Paleozoic aquifers
- Undefined Tertiary, Mesozoic, and Paleozoic units
- Precambrian aquifers
- Confining units

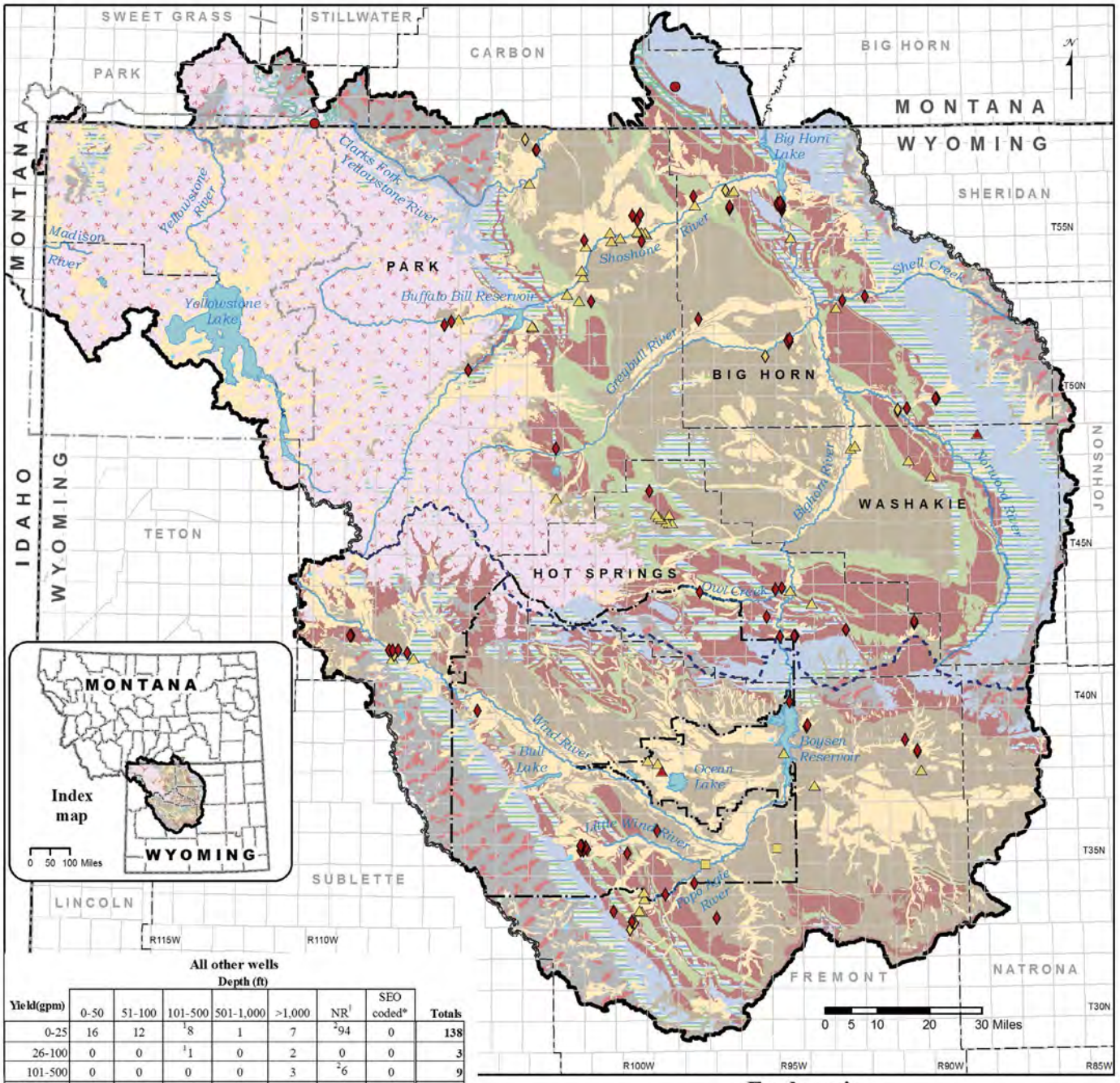
WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Sources:

Montana Bureau of Mines and Geology
Wyoming State Engineer's Office

Figure 8-9. Permitted monitor wells, Wind/Bighorn River Basin.



All other wells

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	16	12	[1]8	1	7	[2]94	0	**138**
26-100	0	0	[1]1	0	2	0	0	**3**
101-500	0	0	0	0	3	[2]6	0	**9**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	1	**1**
Totals	**16**	**12**	**9**	**1**	**12**	**100**	**1**	**151**

New other wells, since 2000

Yield(gpm)	Depth (ft) 0-50	51-100	101-500	501-1,000	>1,000	NR†	SEO coded*	Totals
0-25	2	2	[1]2	0	5	79	0	**90**
26-100	0	0	[1]1	0	0	0	0	**1**
101-500	0	0	0	0	0	2	0	**2**
501-1,000	0	0	0	0	0	0	0	**0**
>1,000	0	0	0	0	0	0	0	**0**
SEO coded*	0	0	0	0	0	0	0	**0**
Totals	**2**	**2**	**3**	**0**	**5**	**81**	**0**	**93**

†NR = Not recorded
*Wells for which a definite depth or yield is not assigned. See Section 8.3.5 for codes.
[1]Data includes Montana wells.
[2]Data includes Wind River Indian Reservation wells.
Note: Reservation wells do not have depth data.
Therefore, all reservation wells are placed in the †NR category.

Explanation

(See Figure 3-1 for explanation of additional symbols)

River
Lake
ice

Hydrogeologic Units
Quaternary aquifers
Absaroka - Yellowstone volcanics
Tertiary aquifers
Mesozoic aquifers
Paleozoic aquifers
Undefined Tertiary, Mesozoic, and Paleozoic units
Precambrian aquifers
Confining units

Well use - by shape
Montana other well
Tribal commercial well
WSEO unknown well
WSEO test well

Well date - by color
Since 2000
Before 2000

WSGS 2011
Projection: NAD 1983
UTM Zone 12N

Data Sources:
Montana Bureau of Mines and Geology
Wind River Indian Reservation
Wyoming State Engineer's Office (WSEO)

Figure 8-10. Other permitted wells, Wind/Bighorn River Basin.

Table 8-8. Montana Bureau of Mines and Geology groundwater permits in the Montana WBRB.

Permit type	*Code*	*Number*	*New since 2000*	*Total permitted yield (gpm)*
Domestic	DOM	38	31	1,457
Stock	STK	6	4	102
Monitor	MON	1	1	4
Other	--	2	2	64
Total		**47**	**38**	**1,627**

can be used to estimate a range of how many wells have actually been drilled in the WBRB by summing status categories 1, 2, 3, and 5 to set a lower limit and including the undefined permits to set an upper limit. Subtracting abandoned permits (category 5) from the range of permits drilled provides a range of likely existing wells in the WBRB. From this analysis, 64 to 76 percent of total permitted wells have actually been installed, 63 to 74 percent of total permits represent active groundwater production, and 42 to 79 percent of wells permitted since 2000 have been installed, with only one recorded abandonment.

8.3.2 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. Similarly to **Table 8-3**, **Tables 8-4** and **8-5** do not include permits from the MBMG or TWE.

Approximately 94 percent of all WSEO groundwater permits for which depth data are available are for wells less than 500 feet deep, and approximately 64 percent are for wells less than 100 feet deep. This trend continued for permits issued from 2000 through June 2009, with an even larger percentage (68%) of permits issued for wells less than 100 feet deep. Many of the permits (54% issued after 2000 and 31% overall) in the WSEO database do not include well depth (**Section 2.4.2**).

Of the 19,444 groundwater permits in the WBRB database for which yield information is available, approximately 95 and 93 percent are for yields of 0-25 gpm for permits issued after 2000 and for total permits, respectively. Fewer than 1 percent of total permits and permits issued after 2000 are for yields greater than 1000 gpm. Fewer than 3 percent of permits issued after 2000 and 4 percent of total permits have been issued for yields greater than 100 gpm.

Permitted depths and yields, and the groundwater-permit locations on **Plates IV and X** illustrate that most wells in the WBRB are planned and completed in near-surface Quaternary and Tertiary hydrogeologic units. This finding confirms that adequate recharge is occurring throughout the WBRB to provide shallow groundwater for a variety of uses.

8.3.3 Groundwater permits by use

Table 8-6 shows the number of WSEO groundwater permits issued through June 2009 for ten primary permitted use categories and "other," which includes all other minor or unique uses. Permit information for the Reservation provided by the TWE is presented in **Table 8-7** by a slightly different list of use categories than those in **Table 8-6**. **Table 8-8** shows the number of MBMG groundwater permits issued through August 2009 by three permitted use categories for the Montana area of the WBRB. Because some permits are issued for more than one use, the total number of permitted uses exceeds the number of permits issued in **Tables 8-6, 8-7, and 8-8**. **Tables 8-9 and 8-10** are expanded summary tables for WSEO municipal-use permits, and **Table 8-11** summarizes information on WDEQ SWAP wells and springs that are used for both municipal and non-community public water supply. A brief discussion of the WDEQ SWAP is provided in **Section 8.3.5.3**. The SWAP provides some information beyond what is available in the WSEO groundwater-permits data.

Tables 8-6, 8-7, and 8-8 show that by far most groundwater permits in the WBRB are for domestic use at individual residences, followed by stock, then monitoring and miscellaneous uses.

8.3.4 Permits by mapped location, depth, yield (Plates IV and X)

Plate IV maps the location of WSEO, TWE, and MBMG permitted groundwater wells and springs compiled for this study overlaid on the surface hydrogeology of the WBRB. Most wells in the WBRB are completed in Quaternary and Tertiary hydrogeologic units. Springs locations were digitized from USGS topographic maps. As discussed previously, many of the permitted wells may not have been installed; in such cases, the location, depth, and yield information in the applications still indicate anticipated groundwater use.

Groundwater-permit statistics are also provided on **Plate IV**, as a table that correlates range of well depth and permitted yield, and a graph of number of permits by use. Consistent with **Tables 8-4 and 8-5**, the depth vs. yield table shows that by far the most permits issued in the WBRB are for 0-25 gpm, across all depth ranges. In addition, the matrix table shows the decrease in the number of wells permitted for increasingly higher yields across all depth ranges

Plate X shows groundwater permits issued from 2000 through June 2009 (these permits are also included on **Plate IV**) in order to evaluate how groundwater development in the WBRB has proceeded over the last decade. Substantial groundwater development has occurred in the WBRB since the previous

Table 8-9. WSEO fully adjudicated groundwater permits for municipal use in the Wyoming WBRB database [DOM, domestic; IND, industrial; IRR, irrigation; MIS, miscellaneous; STK, stock; new since 2000, boldface; aq, aquifer; Fm, Formation; Ls, Limestone; Ss, Sandstone].

Municipality *Well name (other uses)*	*WSEO Permit No.*	*Permit yield (gpm)*	*Well depth (ft)*	*Permit status*	*Producing unit*	*Depth of producing interval (ft)*
Town of Cowley						
MADISON #1	P65794W	850	2300	fully adjudicated	Madison Ls	1,996–2,300
Town of Dubois						
DUBOIS #6	P86868W	100	84	fully adjudicated	alluvium	
DUBOIS #7	P72057W	200	76	fully adjudicated	alluvium	56.0–73.0
DUBOIS NO. 8	P45923W	225	55	fully adjudicated	alluvium	12.0–50.0
DUBOIS #10	P86824W	500	68	fully adjudicated	alluvium	17.0–62.0
Town of Hot Springs						
Road and Bridge, Legion well #1 (IRR)	P3805W	400	13.5	fully adjudicated		
City of Lander						
City of Lander #1	P52717W		2,320	fully adjudicated	Madison Ls	1,118–1,560
Town of Hudson						
HUDSON WELL #1	P1390W	200	22	fully adjudicated	alluvium	
HUDSON #1-A	P45333W	37	45	fully adjudicated	alluvium	
HUDSON #1-B	P45334W	37	45	fully adjudicated	alluvium	
HUDSON #1-C	P45335W	37	45	fully adjudicated	alluvium	
HUDSON # 1-D	P45336W	37	45	fully adjudicated	alluvium	
HUDSON #1-E	P45337W	37	45	fully adjudicated	alluvium	
HUDSON #1-F	P45338W	37	45	fully adjudicated	alluvium	
ENL HUDSON WELL #1	P87401W	65	22	fully adjudicated	alluvium	
HUDSON WELL #2	P1391W	75	27	fully adjudicated	alluvium	19.0–41.0
HUDSON #7	P71922W	25	33	fully adjudicated	alluvium	9.0–20.0
HUDSON #8	P72907W	20	38	fully adjudicated	alluvium	9.0–20.0
HUDSON #9	P72908W	22	39	fully adjudicated	alluvium	9.0–20.0
HUDSON #10	P72909W	20	39	fully adjudicated	alluvium	9.0–20.0
HUDSON #11	P72910W	50	38	fully adjudicated	alluvium	9.0–20.0
Town of Manderson						
MANDERSON WATER WELL #2	P1343W	20	1215	fully adjudicated		
MANDERSON WATER WELL #3	P56800W	65	966.5	fully adjudicated		

Table 8-9 Continued.

Municipality Well name (other uses)	*WSEO Permit No.*	*Permit yield (gpm)*	*Well depth (ft)*	*Permit status*	*Producing unit*	*Depth of producing interval (ft)*
Town of Pavillion						
PAVILLION #1	P1111W	40	495	fully adjudicated	Wind River Fm	476–484
PAVILLION #2	P1112W	45	500	fully adjudicated	Wind River Fm	
PAVILLION #7	P76991W	55	1030	fully adjudicated	Wind River Fm	472–510
NM #4	P59104W	45	510	fully adjudicated	Wind River Fm	480–500
PAVILLION #6	P70972W	30	506	fully adjudicated	Wind River Fm	478–910
City of Riverton						
AIRPORT WELL EDA I	P34941W	450	1400	fully adjudicated	Wind River Fm	
AIRPORT WELL #3	P76404W	725	1823.5	fully adjudicated	Wind River Fm	875–1,750
WWDC, AIRPORT #T3 (MIS)	P26544W	0	0	cancelled		
CITY #12	P806W	325	730	fully adjudicated	Wind River Fm	75–260
CITY #13	P807W	300	700	fully adjudicated	Wind River Fm	94–650
CITY #14	P2430W	400	730	fully adjudicated	Wind River Fm	530–560
FEDERAL #15	P29027W	455	840	fully adjudicated	Wind River Fm	575–804
SUNSET #16	P29028W	535	810	fully adjudicated	Wind River Fm	450–775
Town of Shoshoni						
SHOSHONI #1	P55334W	165	640	fully adjudicated	Wind River Fm	260–560
SHOSHONI #4	P41152W	280	620	fully adjudicated	Wind River Fm	380–595
SHOSHONI #5	P87187W	150	1051	fully adjudicated	Wind River Fm	453–1,015
SHOSHONI #6	P87186W	280	1040	fully adjudicated	Wind River Fm	400–995
Town of Thermopolis						
WELL #1	P81898W	875	30	fully adjudicated	alluvium	
WELL #2	P74205W	400	60	fully adjudicated	alluvium	
WELL #4	P74207W	400	30	fully adjudicated	alluvium	
City of Worland						
Worland #3	P50589W	6000	2334	fully adjudicated		
ENL Worland #3	P71605W	660	2334	fully adjudicated		
3RD ENL. HUSKY-WORLAND NO. 1 WELL (IND, MIS, STK)	**P141305W**	**1028**	**0**	**fully adjudicated**	**Madison Ls**	**2,082–2,756**
Husky Worland #1	P47657W	5000	4210	fully adjudicated		
Totals	***47 – of which 1 is new since 2,000 (boldface)***					

Groundwater Determination (Lidstone and Associates, 2003), and, consistent with the historic trend, most permits issued over the last decade in the WBRB continue to target Quaternary and Tertiary hydrogeologic units.

The depth vs. yield statistics tabulated and graphed on **Plate X** show the same trends identified on **Plate IV,** with most groundwater permits for 0-25 gpm and a decline in the number of permits for higher yields across all depth ranges. Depth and yield are also depicted on **Plate X**, using the well-location symbols. The distribution of permits by depth, and to a lesser degree by yield, is fairly mixed, with shallower and lower-yield wells dominant generally in interior basin areas where flat-lying Quaternary and Tertiary hydrogeologic units are developed. Generally deeper and higher-yielding wells are permitted in the older Mesozoic and Paleozoic units in folded and faulted upland areas surrounding the basins.

8.3.5 Groundwater permits mapped by use, and depth vs. yield statistics (Figures 8-1 through 8-10)

Figures 8-1, 8-2, and 8-4 through 8-10 show the distribution of groundwater permits for the use categories in **Tables 8-6, 8-7, and 8-8** overlaid on an abridged version of the surface hydrogeology map (**Plate IV). Figure 8-3** shows the distribution of SWAP wells and springs that are used for municipal, domestic, and public supply. Because public supply is one of the most important uses of groundwater resources, a more comprehensive compilation was performed for the WSEO permit data and related WDEQ SWAP data on municipal and other (non-community) public supply wells and springs. Tables of depth vs. yield for the total number of permits and permits since 2000 are included on each of the **Chapter 8** maps, and permits issued before and after 2000 are distinguished by well-location symbols. In some cases, non-specific depth or yield information is "coded" (included in the total, but not in a category):

1 – unknown
4 – artesian flowing at surface
5 – pit
6 – artesian not flowing above ground surface
7 – dry

8.3.5.1 WSEO municipal-use permits (Figure 8-1)

Figure 8-1 shows the distribution of WSEO permits for municipal and Tribal public use in the WBRB. Consistent with **Tables 8-6 and 8-7,** the depth vs. yield tables on **Figure 8-1** show **133 WSEO permits** of which **13** were installed from January 2000 through June 2009. Most municipal permits are for yields ranging to 500 gpm, distributed across depths ranging to more than 1000 feet. Most permits since 2000 are for depths greater than 1,000 feet and for yields greater than 1,000 gpm **(5)** and for 25 gpm or less **(5)**. No municipal-use permits were included in the MBMG data.

Tables 8-9 and 8-10 distinguish the **130** municipal-use groundwater permits on file with the WSEO by status. **Table 8-9** summarizes selected information on **44** municipal-use permits that have been fully adjudicated. Three of the permits in **Table 8-9** are for multiple uses. Most of the permits in **Table 8-9** include information on yield, well depth, depth of the producing interval, and the producing hydrogeologic unit. As fully adjudicated groundwater appropriations by definition indicate that the well has been inspected, the information in **Table 8-9** (for which information on producing interval was obtained from WDEQ SWAP data) is presumed to be fairly accurate. The wells in **Table 8-9** produce water from alluvial aquifers, the Wind River aquifer in the (Wind River Basin), or the Madison-Bighorn aquifer in the Bighorn Basin and corresponding Paleozoic aquifer system units in the WRB **(Plates II and III)**.

Table 8-10 summarizes the same information as that in **Table 8-9** for **83** incomplete, cancelled, abandoned, and undefined WSEO permits. **Fifteen** of the permits in **Table 8-10** are for multiple uses. While cancelled permits may or may not be associated with a completed well, abandoned status generally refers to a previously existing well. Most of the **Table 8-10** permits include yield and well depth; however, only fifteen include the producing hydrogeologic unit (alluvial aquifers, the Wind River aquifer, and the Madison-Bighorn aquifer). Permits with the most information, especially those that include the depth of the producing interval (which is generally provided by the well owner after the well has been completed) are most likely to be associated with completed wells and may provide actual use volume.

8.3.5.2 Domestic-use permits (Figure 8–2)

Domestic water withdrawals include non–community public water systems and rural domestic users. **Tables 8-6, 8-7, and 8-8** show that groundwater permits for domestic use outnumber permits for all other uses combined, with **12,876** WSEO permits, **627** TWE permits, and **38** MBMG permits.

Figure 8-2 shows the distribution of domestic-use permits in the WBRB. Most domestic wells are in rural areas, including areas where groundwater is the sole reliable source of water. Wells are located mostly along rivers and other surface drainages within the interior basins, completed primarily in Quaternary and Tertiary geologic units. A smaller number of domestic-use permits are associated with population centers. The depth vs. yield tables on **Figure 8-2** show that by far most of groundwater permits are for depths of 500 feet or less and yields to 25 gpm for both total permits and permits issued since 2000. More than one-third of domestic-use permits are coded or have no recorded depth; a much smaller number (**43)** have coded yield information. **Figure 8-2** also shows that domestic-use wells have been mostly permitted at relatively shallow depth within

Table 8-10. WSEO incomplete, cancelled, abandoned, and permits with no listed status in the Wyoming WBRB database by municipal use.
[DOM, domestic; IND, industrial; IRR, irrigation; MIS, miscellaneous; STK, stock; new since 2000, boldface; aq, aquifer; Fm, Formation; Ls, Limestone; Ss, Sandstone].

Municipality Well Name (other uses)	*WSEO Permit No.*	*Permit yield (gpm)*	*Well depth (ft)*	*Permit status*	*Producing unit*	*Depth of producing interval (ft)*
Town of Burlington						
BURLINGTON #1	P72148W/ P72149W	500	42	cancelled	alluvium	
BURLINGTON #1	P72977W			abandoned		
BURLINGTON #2	P72978W	100	41	abandoned	alluvium	
BURLINGTON WELL #3	P77827W		48		alluvium	25.0–35.0
Town of Byron						
ENL MADISON #1	P70335W	0	2300	cancelled		
TOWN OF BYRON	P45996W	1200	13.5	cancelled		
Town of Cody						
Valley View Water Well #1	P793W	15	30	cancelled		
Town of Deaver						
#1	P66522W	300	0	cancelled		
Town of Dubois						
DUBOIS WATER SYSTEM WELL #2	P224W	70	47			
DUBOIS DOWNTOWN #3	P1721W	300	25			
DUBOIS WATER SYSTEM WELL #3	P225W	250	50	abandoned		
DUBOIS #4	P2108W	150	47	abandoned		
DUBOIS DOWNTOWN #5	P36138W	900	0	cancelled		
DUBOIS WELL #9	P31790W	800	0	cancelled		
DUBOIS #9	P72056W	100	51	cancelled		
DUBOIS NO. 11	**P178782W**	**1200**	**0**			
YARBOROUGH #5	P27269W	30	40	cancelled		
Town of Frannie						
ENL Frannie Unit #136	P123649W	0	0	cancelled		
Town of Greybull						
UNDERGROUND #1	P8426W	1000	0	cancelled		
WWDC, Greybull #1 (MIS)	P62476W	85	3250	cancelled	Madison–Bighorn aq.	2,450–3,250
WWDC, ENL. Shell Valley #1 Well (MIS)	**P179086W**	**0**	**3379**		**Madison Ls**	**1,850–2,440**
WWDC, ENL. Shell #2 Well (MIS)	**P179087W**	**0**	**3379**	**incomplete**	**Madison Ls**	**2,646–2,940**
Shell Valley #2	P75583W	1200	3379			
WWDC, ENL. Shell #3 Well (MIS)	**P179088W**	**0**	**2051**		**Madison–Bighorn aq.**	**1,055–2,051**

Table 8-10. Continued.

Municipality Well Name (other uses)	*WSEO Permit No.*	*Permit yield (gpm)*	*Well depth (ft)*	*Permit status*	*Producing unit*	*Depth of producing interval (ft)*
WWDC Shell #3 (MIS)	P102870W	1000	2051	incomplete		
Town of Kirby						
Town of Kirby well #3	P74046W	40	670			
WELL #1 (DUG)	P1632W	450	15	cancelled		
WELL #1	P77215W	20	60			
WELL #2 (DUG)	P1633W	55	15			
WELL #2	P77217W	25	0	cancelled		
WELL #3	P82092W	20	156	incomplete		
WELL #4	P78034W	20	140	incomplete		
WELL #5	P77908W	20	200			
WELL #6	P77909W	20	110			
WELL #7	P78026W	12	200	incomplete		
WELL #8	P77910W	20	200			
WELL #9	P78027W	20	0	cancelled		
WELL #10	P78028W	20	130			
WELL #11	P78029W	20	160			
WELL #12	P78030W	20	160	incomplete		
WELL #13	P78031W	20	130			
WELL #14	P78032W	20	160	incomplete		
WELL #15	P91102W	40	210	cancelled		
WELL #15	P78033W		0			
City of Lander						
LANDER FIELD #F1	P42336W	400	0	cancelled		
LANDER FIELD #F2	P42337W	400	0	cancelled		
LANDER FIELD #F3	P42338W	400	0	cancelled		
Lander Well Treatment Plant 3A	**P134639W**	**0**	**85**		**alluvium**	**56.0–75.0**
City of Lander #2	P28663W					
Lander City golf course #1 (IRR)	P6071W	100	0	cancelled		
Hartnett #1 (DOM, IND, IRR)	P943W	50	0	cancelled		
City of Lander #1	P31247W	1000		cancelled		
Town of Lovell						
LOVELL #1	P50274W	0	0	cancelled		
Town of Manderson						
WWDC, Manderson Wild Horse #1(MIS)	**P99757W**	**270**	**5419**	**incomplete**	**Madison Ls**	**5,029–5,332**
WWDC, ENL. Manderson Wild Horse #1 Well (MIS)	P179084W	55	5419		Madison Ls	
Ormsbee Development Co.						
MIMAR #1	P557W	30	110			

Table 8-10. Continued.

Municipality Well Name (other uses)	*WSEO Permit No.*	*Permit yield (gpm)*	*Well depth (ft)*	*Permit status*	*Producing unit*	*Depth of producing interval (ft)*
MIMAR #2	P558W	30	110			
MIMAR #3	P559W	30	110			
Town of Pavillion						
PAVILLION #7	P73491W	25	515	cancelled		
PAVILLION #8	P98757W	30	517	incomplete	Wind River Fm	504–512
ENL PAVILLION #8	P102274W	35	517	incomplete		
S #5	P62641W	0	705	abandoned	Wind River Fm	
TOP #3	P34345W	40	510	cancelled		
City of Riverton						
WELL #17	**P180221W**	**400**	**0**			
WELL NO. 17	**P151725W**	**325**	**0**			
SUNSET #T 4	P26814W	–1	–1	abandoned		
HONOR FARM MUNICIPAL WELL #1	P104356W		870	incomplete	Wind River Fm	486–783
Airport well #3	P71844W	450		cancelled		
Town of Shoshoni						
Shoshoni #2	P13818W/ P55335W	150		cancelled		
Shoshoni #3	P13819W	150		cancelled		
Town of Ten Sleep						
WATER WELL #2	P40517W	2000	1098	cancelled	Madison Ls	860–1,098
Town of Thermopolis						
Town of Thermopolis Well #1	P74204W	600		cancelled		
Red Lane watershed improvement district, Sacajawea (DOM, IRR, STK)	P1874W	–1	1200	cancelled		
City of Worland						
Worland #2	P50588W	6000				
Worland #4	P50590W	6000				
ENL Husky #1 (STK)	P71604W	200	4210	cancelled		
WWDC, 4th ENL. Husky–Worland #1 Well (MIS)	**P179083W**	**3465**	**4210**			
WWDC, ENL. Wild Horse #2 (MIS)	P179085W	0	5351			
WWDC, Wild Horse #2 (MIS)	**P100870W**	**150**	**5351**	**incomplete**		
3RD ENL. WORLAND NO. 3 WELL (IND, MIS, STK)	**P141306W**	**1028**	**0**			
WWDC, 4th ENL. Worland #3 Well (MIS)	**P179082W**	**3465**	**2334**		**Madison Ls**	**2,236–2,334**
Totals	***83 – of which 12 are new since 2000 (bold face)***					

Table 8–11. Wyoming Department of Environmental Quality SWAP wells and springs.
[DOM, domestic; IND, industrial; IRR, irrigation; MIS, miscellaneous; STK, stock; new since 2000, boldface; aq, aquifer; Fm, Formation; Ls, Limestone; Ss, Sandstone].

Municipality WellName	***Public Water System Well ID***	***WSEO Permit No.***	***Yield (gpm)***	***Well depth (ft)***	***Source type***	***Producing unit***
Town of Burlington						
BURLINGTON WELL #3	5601098–102	P79233W	85	45	Well	alluvium
BURLINGTON WELL #4	5601098–101	P77827W	85	45	Well	alluvium
Town of Cowley						
MADISON #1	5600206–101	P65794W	850	2300	Well	Madison Ls
Town of Dubois						
DUBOIS WATER SYSTEM WELL #3	5600177–105	P225W	250	50	Well	alluvium
DUBOIS #6	5600177–101	P86868W	100	84	Well	alluvium
DUBOIS #7	5600177–104	P72057W	200	76	Well	alluvium
DUBOIS #8	5600177–102	P45923W	225	55	Well	alluvium
DUBOIS #9	5600177–103	P72056W	100	51	Well	alluvium
DUBOIS #10	5600177–111	P86824W	500	68	Well	alluvium
Town of Greybull						
GREYBULL #1 (GREY WELL)	5600022–105	P62476W	85	3250	Well	Madison–Bighorn aq.
SHELL #3	5600022–104	P102870W	1000	2051	Well	Madison–Bighorn aq.
Town of Hudson						
Well #2	5600183–101–thB	P45334W	37	45	Well	alluvium
Well #3	5600183–101–thC	P45335W	37	45	Well	alluvium
Well #4	5600183–101–thD	P45336W	37	45	Well	alluvium
Well #5	5600183–101–thE	P45337W	37	45	Well	alluvium
Well #6	5600183–101–thF	P45338W	37	45	Well	alluvium
Well #7	5600183–102–thA	P71922W	25	33	Well	alluvium
Well #8	5600183–102–thB	P72907W	20	77	Well	alluvium
Well #9	5600183–102–thC	P72908W	22	39	Well	alluvium
Well #10	5600183–102–thD	P72909W	20	39	Well	alluvium
Well #11	5600183–102–thE	P72910W	50	38	Well	alluvium
City of Lander						
LANDER WELL TREATMENT PLANT 3A	5600176–105	P134639W	0	85	Well	alluvium
LANDER WELL TREATMENT PLANT 3A – Consecutive	5600805–105	P134639W	0	85	Well	alluvium
CITY OF LANDER #1	5600176–103	P52717W	130	2320	Well	Madison Ls
CITY OF LANDER #1 – Consecutive	5600805–103	P52717W	130	2320	Well	Madison Ls

Table 8–11. Continued.

Municipality WellName	*Public Water System Well ID*	*WSEO Permit No.*	*Yield (gpm)*	*Well depth (ft)*	*Source type*	*Producing unit*
Town of Manderson						
MANDERSON WILD HORSE #1	5601454–101	P99757W	270	5419	Well	Madison Ls
MANDERSON WILD HORSE #1 – Consecutive	5600204–104	P99757W	270	5419	Well	Madison Ls
WILD HORSE #2	5601454–102	P100870W	150	5351	Well	Madison Ls
WILD HORSE #2 – Consecutive	5600204–105	P100870W	150	5351	Well	Madison Ls
MANDERSON WATER WELL #2	5600204–103	P1343W	20	1215	Well	Madison Ls
MANDERSON WATER WELL #3	5600204–102	P56800W	65	966	Well	Madison Ls
Town of Pavillion						
TOWN OF PAVILLION #1	5600039–101	P1111W	40	495	Well	Wind River Fm
TOWN OF PAVILLION #2	5600039–102	P1112W	45	500	Well	Wind River Fm
PAVILLION #6	5600039–104	P70972W	30	506	Well	Wind River Fm
PAVILLION #7	5600039–105	P76991W	30	515	Well	Wind River Fm
Well #8	5600039–106	P98757W	30	517	Well	Wind River Fm
City of Riverton						
AIRPORT WELL #2	5600047–113	P34941W	450	1400	Well	Wind River Fm
AIRPORT WELL #3	5600047–102	P76404W	275	1823	Well	Wind River Fm
CITY #12	5600047–106	P806W	325	730	Well	Wind River Fm
CITY #13	5600047–108	P807W	300	700	Well	Wind River Fm
CITY #14	5600047–112	P2430W	400	730	Well	Wind River Fm
FEDERAL #15	5600047–111	P29027W	455	840	Well	Wind River Fm
SUNSET #16	5600047–104	P29028W	535	810	Well	Wind River Fm
Honor Farm Well	5600047–114	P104356W	400	1150	Well	Wind River Fm
BURCH #4	5600047–110	P11G	475	600	Well	Wind River Fm
FENTON #3	5600047–107	P12G	200	609	Well	Wind River Fm
HIBER #6	5600047–109	P9G	225	645	Well	Wind River Fm
RYAN HEIGHTS #9	5600047–105	P250C	150	605	Well	Wind River Fm
RESERVOIR #11	5600047–103	P214G	225	994	Well	Wind River Fm
Town of Shoshoni						
SHOSHONI #1 (WELL #2)	5600053–101	P55334W	175	640	Well	Wind River Fm
WELL #3 TOWN OF SHOSHONI	5600053–103	P35G	50	446	Well	Wind River Fm
SHOSHONI #2	5600053–102	P55335W	150	580	Well	Wind River Fm
SHOSHONI #4	5600053–104	P41152W	280	620	Well	Wind River Fm
SHOSHONI #5	5600053–105	P87187W	150	1051	Well	Wind River Fm
SHOSHONI #6	5600053–106	P87186W	280	1040	Well	Wind River Fm
Town of Ten Sleep						
TEN SLEEP #1	5600203–101	P368G	350	1050	Well	Darwin Ss and Madison Ls
TEN SLEEP #2	5600203–102	P48580W	500	1098	Well	Madison Ls
Town of Thermopolis						

Table 8–11. Continued.

Municipality WellName	*Public Water System Well ID*	*WSEO Permit No.*	*Yield (gpm)*	*Well depth (ft)*	*Source type*	*Producing unit*
WELL NO 1	5600056–101	P81898W	275	30	Well	Quaternary alluvium
WELL NO 1 – Consecutive	5601083–101	P81898W	275	30	Well	
WELL NO 2	5600056–102	P74205W	400	60	Well	Quaternary alluvium
WELL NO 2 – Consecutive	5601083–102	P74205W	400	60	Well	
WELL NO 3	5600056–103	P74207W	400	30	Well	Quaternary alluvium
WELL NO 3 – Consecutive	5601083–103	P74207W	400	30	Well	
City of Worland						
WORLAND #3	5600197–102	P50589W	6000	2334	Well	Madison Ls
HUSKY WORLAND #1	5600197–101	P47657W	5000	4210	Well	Madison Ls
Wells without known Municipality						
[unnamed]	**5600983–101**	**Unknown (spring?)**			**Spring**	**landslide deposits**
#1 AMERICAN COLLOID	5601252–105	P22667W	5	18	Well	alluvium
#2 CAR GARDGE	5601482–101	P82799W	40	500	Well	Wind River Fm
3 MILE CG WELL W #1	5680017–101	P113529W	0	62	Well	Shoshone River gravels
ABSAROKA MTN LODGE #1	5600467–101	P91381W	23	108	Well	
ACC WELL #2	5601252–104	P22668W			Well	alluvium
ACC WELL #6	5601252–102	P98546W	15	22	Well	alluvium
ACC WELL #7	5601252–101	P102677W	40	35	Well	alluvium
AMERICAN COLLOID #3	5601252–103	P58922W	1000	40	Well	alluvium
ANDREWS #2	5601225–101	P42911W	100	446	Well	Wind River Fm
B. C. #1	5600744–102	P83761W	20	65	Well	Powell Terrace
BCU WATER WELL #26	5601185–101	P1350W	75	113	Well	Wind River Fm
BEARTOOTH CAMPGROUND #1	5680237–101	P62852W	10	75	Well	Oldest Gneiss Complex
BEARTOOTH CAMPGROUND #2	5680237–102	P62850W	10	105	Well	Oldest Gneiss Complex
BOAT CLUB #2	5600744–101	P83759W	40	75	Well	Powell Terrace
BOULDER PARK CAMPGROUND SPRING	5680004–101				Spring	glacial deposits
BRUNNER WELL #1	5600860–101	P13303W	25	40	Well	alluvium
BRUNO #1	5600464–101	P76248W	5	40	Well	
Bull Lake Cr. #1	5601042–101	P71841W	20	340	Well	Wind River Fm.
BUS GARAGE	5601482–102	P84081	24	515	Well	Wind River Fm
CASTLE ROCK CENTRE #3	5601237–105	P74740W	10	80	Well	
CIRCLE J #1	5601165–101	P59450W	25	35	Well	
CIRCLE J #2	5601165–103	P59451W	20	30	Well	

Table 8–11. Continued.

Municipality WellName	*Public Water System Well ID*	*WSEO Permit No.*	*Yield (gpm)*	*Well depth (ft)*	*Source type*	*Producing unit*
CIRCLE J #3	5601165–102	P59452W	25	30	Well	
CITY #14	5600047–112	P2430W	400	730	Well	Wind River Fm
CLARK SCHOOL #2	5601059–101	P71369W	20	70	Well	alluvium
CODY KOA #1	5601372–102	P42283W	32	50	Well	
COTTONWOOD BAY WELL #2	**5600659–101**	**P139251W**	**25**	**740**	**Well**	**Wind River Fm**
COY #1	5601219–102	P74837W	20	107	Well	
CWC FIELD STATION #1	5601366–101	P80820W	25	77	Well	alluvium
DEER HAVEN SPRING	5600565–101	P22167D			Spring	glacial deposits
EAGLE CREEK CG EAST	5680216–101	P62861W	10	55	Well	Shoshone River gravels
EAGLE CREEK CG MIDDLE	5680217–101				Well	Shoshone River gravels
EAGLE CREEK CG WEST	5680218–101	P62854W	10	55	Well	Shoshone River gravels
ENL BUFFALO BILL BOY SCOUT WELL #1	5601373–101	P69123W	195	15	Well	alluvium/ colluvium
FIRST FIKE #1	5600194–101	P31920W	20	340	Well	Wind River Fm
FISHING BRIDGE SPRING	5680079–102				Spring	undivided surficial deposits and rhyolite flows
FIVE SPRINGS CAMPGROUND	5680240–101	P68662W	2	69	Well	landslide deposits
FREMONT BAY WELL #2	**5600658–101**	**P139250W**		**640**	**Well**	**Wind River Fm**
GAINES #1	5600180–101	P35482W	25	180	Well	Wind River Fm
GAINES #2	5600180–102	P35651W	60	180	Well	Wind River Fm
GARDENS NORTH #1	5600774–101	P48745W	125	400	Well	Wind River Fm
GEORGIA PACIFIC #2	5600611–102	P68485W	120	1213	Well	
GEORGIA PACIFIC #3	5600611–103	P75007W	40	100	Well	
GOOSEBERRY #3	**5601194–101**	**P78289W**	**5**	**1792**	**Well**	**Fort Union Fm**
HALLETT #4	5601275–101	P91732W	0		Well	Tensleep Fm
HART #1	5600861–101	P98368W	200	712	Well	
HIMES #1	5600611–101	P5878W	80	1125	Well	
HRUZA #1	5600175–101	P33113W	25	61	Well	alluvium
HYATTVILLE #1	5600209–101	P2186W	130	2895	Well	Madison Ls
INDIAN CREEK CG WELL	5680078–101				Well	undivided surficial deposits
KOA #1	5600702–101	P23722W	15	60	Well	
K–Z #1	5600448–101	P99148W	5	100	Well	
L. B. HORN WATER WELL #1	5600228–102	P2224W	63.6	25	Well	
LAKE SPRING	5680079–101				Spring	undivided surficial deposits and rhyolite flows
LAMAR SPRING	5680080–101				Spring	undivided surficial deposits

Table 8–11. Continued.

Municipality WellName	*Public Water System Well ID*	*WSEO Permit No.*	*Yield (gpm)*	*Well depth (ft)*	*Source type*	*Producing unit*
LEIGH CREEK DUMP STATION	**5601539–101**	**P145525W**			**Well**	**Oldest Gneiss Complex**
LODGE SPRING	5601400–101	32/4/27D			Spring	Aycross Fm
LOWER WIND RIVER #1	5600656–101	P25988W	25	100	Well	alluvium
MADISON SPRING	5680082–101				Spring	rhyolite flows, tuff, and intrusive igneous rock
MEADOWLARK LAKE LODGE WELL #2	5600362–101	P92722W	25	80	Well	
MEDICINE LODGE #1	5600979–101	P33514W	25	60	Well	alluvium
MOUNTAIN VIEW ACRES #1	5600182–101	P34939W	60	575	Well	Wind River Fm
MOUNTAIN VIEW ACRES #2	5600182–102	P57548W	34	455	Well	Wind River Fm
NEWTON CREEK #12	5680221–101				Well	Shoshone River gravels
NIPPER #1	5600179–101	P42159W	20	210	Well	Wind River Fm
NIPPER #2	5600179–102	P32724W	40	260	Well	Wind River Fm
NIPPER #3	5600179–103	P42160W	20	190	Well	Wind River Fm
NM #4	5600039–103	P59104W	45	510	Well	Wind River Fm
NORRIS WELL #1	5680084–101				Well	undivided surficial deposits
NORRIS WELL #2	5680084–102				Well	undivided surficial deposits
NORRIS WELL #3	5680084–103				Well	undivided surficial deposits
NORTH END WATER USERS #2	5600043–102	P29189W	250	50	Well	terrace and alluvium
NORTH END WATER USERS #3	5600043–103	P94521W	300	65	Well	terrace and alluvium
NORTH END WATER USERS WELL #1	5600043–101	P1416W	250	40	Well	terrace and alluvium
NORTH FORK CAMPGROUND #1	5600667–101	P76421W	25	88	Well	alluvium
NORTH SHORE BAY CAMPGROUND #1	5601268–101	P101958W			Well	Shoshone River gravels
PAHASKA CAMPGROUND	5600439–101	P62862W	10	55	Well	
PINNACLE RANCH #1	5600407–101	P90819W	100	35	Well	
RANGER CREEK CAMPGROUND	5680243–101	P71210W	5	60	Well	glacial deposits
REX HALE CAMPGROUND	5680224–101	P62857W	10	55	Well	Shoshone River gravels
SECOND FIKE	5600195–101				Well	Wind River Fm
SEVEN D #1	5600566–101	P31265W	25	145	Well	
SHELL FALLS SPRING	5680008–101				Spring	landslide deposits and Bighorn Dolomite

Table 8–11. Continued.

Municipality WellName	*Public Water System Well ID*	*WSEO Permit No.*	*Yield (gpm)*	*Well depth (ft)*	*Source type*	*Producing unit*
SHELL VALLEY #1 (SHELL #1)	5600022–103	P75584W	300	2440	Well	Madison Ls
SHELL VALLEY #2 (SHELL WELL #2)	5600022–102	P75583W	1200	3379	Well	Madison Ls
SINKS CAMP UPPER NO. 1	5680201–101	P27263W	25	60	Well	alluvium
SINKS CANYON STATE PARK HQ #1	5601190–101	P81368W	10	151	Well	alluvium
SITTING BULL CAMPGROUND WELL	5680005–101	P92153W	5	200	Well	Oldest Gneiss Complex
SPENCER #1	5600184–101	P26444W	20	175	Well	Wind River Fm
SPENCER #2	5600184–102	P459W	10	60	Well	Wind River Fm
SPENCER WELL #1	5600173–101	P406C	50	300	Well	Wind River Fm
SPRING	5601407–101				Spring	Oldest Gneiss Complex
STATE LAND WATER WELL #1	5600228–101	P2225W	35	698	Well	
TIMBERLINE UPPER RANCH WELL #1	5600933–101	P68341W	7	120	Well	
TOWER FALLS SPRING	5680089–101				Spring	undivided surficial deposits and rhyolite flows
TOWER JUNCTION SPRING	5680090–101				Spring	undivided surficial deposits
TOWNSEND CREEK SPRING	5600389–101	P22750D			Spring	Louis Lake Pluton
TUFF WELL #2	5601189–101	P72676W	5	121	Well	Wind River Fm
TYRELL RANGER STATION	**5601009–101**	**P114264W**	**10**	**240**	**Well**	**glacial deposits**
UPPER WIND RIVER #2	5600655–101	P72677W	25	100	Well	alluvium
VALLEY FARMS #2	5601193–101	P60148W	20	68	Well	Meeteetse Fm
Wapiti Campground well #1	5680019–101				Well	Shoshone River gravels
WAPITI SCHOOL #1 WELL	5600571–101	P87741W	20	70	Well	landslide deposits
Well #1	5600183–101–thA	P45333W	37	45	Well	alluvium
WELL #1	5680086–101				Well	undivided surficial deposits
WELL #1	5680152–101				Well	undivided surficial deposits
WELL #2	5680086–102				Well	undivided surficial deposits
WELL #2	5680152–102				Well	undivided surficial deposits
[unnamed]	5600175–102				well	alluvium
[unnamed]	5601337–101					terrace and alluvium
[unnamed]	5601141–101	P42882				
[unnamed]	5601240–103	P71754				
Totals	***177***	***146 – of which 6 are new since 2000 (boldface)***				

virtually all hydrogeologic units (including confining units) throughout the WBRB, illustrating that useful quantities of relatively shallow groundwater can be found at many locations and confirming that recharge is widespread within the WBRB.

8.3.5.3 Source Water Assessment Program (SWAP) wells and springs (Figure 8-3)

The SWAP, a component of the federal Safe Drinking Water Act designed to help states protect public water systems (PWSs), applies to both municipal and non-community public systems. 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), for groundwater PWSs. A source-water assessment entails determining the source-water contributing area, inventorying potential sources of contamination to the PWS(s), determining the susceptibility of the PWS(s) to identified potential contaminants, and summarizing the information in a report. An important aspect of these reports relative to this study is that the producing hydrogeologic unit is commonly identified. As discussed in **Section 5.7.2**, the individual PWS reports are also a good source of information on potential local area contaminant sources and other information on specific groundwater sources. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming. Additional information on the SWAP in Wyoming can be accessed at

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

Copies of the Source Water Assessment Reports for specific PWS systems in the WBRB can be accessed at

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

Figure 8-3 shows the distribution of WDEQ SWAP wells and springs in the WBRB. The depth vs. yield tables on **Figure 8-3** show **177** SWAP wells, **6** of which were constructed after January 2000. Most SWAP wells and springs are for yields ranging to 500 gpm distributed across depths ranging to more than 1000 feet. Most of the SWAP wells have associated WSEO permit number, yield, and depth.

Table 8-11 provides information on **177** SWAP wells and springs, seven of which provide water for more than one PWS (labeled "consecutive" in **Table 8-11**). Most **(146)** of the wells and springs listed in **Table 8-11** have WSEO permit numbers. **Twenty one** wells and springs in the SWAP data do not include WSEO permit numbers, yield, or well depth. Several of the SWAP wells and springs with WSEO permit numbers are not found in the WSEO data. These permits were either not included during transfer to a new database system or otherwise not included. Limitations of the WSEO database are discussed in **Section 2.4 and Appendix C**. A notable feature of **Table 8-11** is that in addition to alluvial aquifers, the Wind River aquifer, and the Madison–Bighorn aquifer, many geologic units are identified as producing units, including a wider range of Quaternary and Tertiary (surficial) deposits and various volcanic and Precambrian units.

8.3.5.4 Industrial and mineral use and CBNG permits (Figures 8-4 and 8-5)

Tables 8-6 and 8-7 show that as of June 2009, **349** permits for industrial and mineral (IND) use, including **8** from the TWE data (MIN), and **27** coalbed natural gas (CBNG) permits had been issued in the WBRB. Industrial use in the WSEO data covers a wide range of sub-categories. Examples of self-supplied general industrial facility operational use for groundwater include fabrication, processing, washing, and cooling. Groundwater use for non-fuels mining includes extraction, milling (crushing, screening, washing, flotation), and other activities associated with producing and processing metallic and industrial mineral ores and stone, sand, and gravel. Groundwater use for fuels mining includes the production of uranium, coal, petroleum, and natural gas. Groundwater withdrawn for industrial and both non-fuels and fuels mining operations is also commonly reused for general industrial purposes such as dust control. Specific industrial uses are not identified in the WSEO-compiled database; the individual permits must be examined. A full review of all permits was beyond the scope of this project, but the smaller number of fully adjudicated industrial- and mineral-use permits was reviewed to illustrate common sub-categories, with the following results:

- 31 for injection, primarily for enhanced oil and gas recovery
- 7 for gypsum wallboard production
- 6 for uranium mill processing
- 1 for gas processing
- 1 for sodium chloride and potassium chloride processing
- 1 for mixing concrete
- 1 for fire suppression, drinking water, general use, and dust suppression (uranium mine)
- 1 for light industrial/commercial use and drinking water
- 1 for drinking water for a trailer subdivision

Figures 8-4 and 8-5 show the distribution of industrial, mineral, and CBNG permits in the WBRB, permits issued before and after 2000, and Tribal Water Engineer (TWE) permits. Most industrial and mineral wells in the WBRB are clustered in rural areas around conventional oil and gas fields

(**Figure 5-3**) and a former uranium mining area in the Gas Hills (**Figures 5-7 and 5-9**). Industrial developments are mostly located at lower elevations around the perimeter of the basins within Mesozoic and Tertiary outcrop areas. Fewer wells are located within interior areas of the basins in Quaternary and Tertiary outcrop areas. The few CBNG wells in the WBRB are completed in Tertiary Fort Union coal beds in the Wind River Basin and in Cretaceous Mesa Verde coals in the Bighorn Basin.

The depth vs. yield tables on **Figure 8-4** show that industrial/mineral groundwater permits have been issued over a range of depths to greater than 1000 feet, with most permitted yields to 500 gpm for both total permits and permits issued since 2000. Approximately half the industrial/mineral–use permits are coded or have no recorded depth, **43** have coded yield information, and none of the TWE data include depth. The depth vs. yield tables on **Figure 8-5** show that all the CBNG wells are permitted by the WSEO for 100 gpm and that all but four have no recorded depth. Most of the CBNG permits have been issued since 2000.

8.3.5.4.1 Groundwater use for energy development

Groundwater produced during energy development constitutes most withdrawal for industrial and mining (WSEO–IND) use and also accounts for most total withdrawal for all uses **(Table 8-2c).** Withdrawal in this category in the WBRB is primarily associated with conventional oil and gas operations, with lesser amounts for CBNG and historic uranium and coal mining. In conventional oil and gas production, groundwater is produced as a byproduct and mostly disposed of by various methods; a smaller amount is used beneficially in processing or associated operational activities (e.g., drilling, dust suppression). In contrast, groundwater extraction is integral to CBNG operations because the hydraulic pressure in the host coal beds must be lowered to liberate dissolved and adsorbed methane, and groundwater flow functions to transport the gas phase to production wells. Therefore, groundwater production for CBNG production is considered a beneficial use in Wyoming, and permitting by the WSEO is required in addition to permitting of gas production by the WOGCC or BLM, depending on mineral ownership. Permits for CBNG withdrawals are, therefore, included in the WSEO database compiled for this project, while produced water withdrawals from conventional oil and gas operations are not, unless the water is put to a beneficial use. Information on produced water associated with conventional oil and gas operations and additional information on CBNG wells may be obtained from the WOGCC office in Casper or from their website,

http://wogcc.state.wy.us/

CBNG development in the WBRB has been insignificant compared with that in other basins (20 wells in the Wind River Basin, none in the Bighorn Basin); however, coal seams with CBNG production potential are present in the WBRB, and it is likely that coalbed groundwater and methane production will increase in the future. Groundwater production on the order of 5–15 gpm per well is generally required for efficient CBNG production. CBNG operations produce (use) an estimated 940 acre-feet of groundwater annually in the WBRB. To date, approximately 2,532 acre-feet of groundwater have been withdrawn during CBNG operations in the WBRB (pers. comm., WOGCC, 2011).

Figure 5-3 shows the locations of conventional oil and gas fields in the WBRB, where groundwater is produced in very large volumes as a byproduct. Conventional oil and gas operations in the WBRB produce an estimated 582 acre-feet of fresh and 90,451 acre-feet of saline groundwater each year (**Table 8-2c**). Approximately 151,364 acre-feet of groundwater was produced in 2009, and 4,178,445 acre-feet has been produced to date (pers. comm., WOGCC, 2011). Options for managing produced water (including CBNG water) as allowed by the quality and the volume of the water produced, include:

- Underground injection for storage, permanent disposal, or enhanced recovery (water flooding, pressure maintenance)
- Infiltration from unlined pits and subsurface structures (tinhorns and other Class V injection facilities)
- Evaporation from pits, landspreading, and landfarming
- Surface discharge for surface flows and associated uses:
    - domestic use (rare)
    - wildlife and livestock watering
    - wetlands, fish, and other aquatic wildlife habitat maintenance
    - irrigation
- General industrial uses:
    - drilling
    - road application and dust control
    - fire control
    - washing
    - power generation

Figures 5-3 and 5-4 show the location of Class II and Class I injection wells that can inject produced water from oil and gas operations for a variety of purposes. The WOGCC, BLM, and EPA permit Class II wells to operators for disposal of their own produced water. The WDEQ permits Class I wells for disposal of non-hazardous wastewaters from a variety of sources. The WOGCC and BLM also permit evaporation pits to operators for disposal of their produced water, generally in the field

where the water was produced (**Figure 5-3**). **Figure 5-4** also shows the location of commercial disposal pits where produced water and other non-hazardous water (by RCRA criteria) from a variety of sources can evaporate.

Produced water of suitable quality can be put to beneficial use (e.g., stock, agriculture, drilling, dust suppression). Otherwise, produced water is primarily discharged to the surface under WDEQ NPDES/WYPDES permit, re-injected for enhanced recovery of oil and gas from depleted reservoirs (also a beneficial use), or re-injected strictly as a means of disposal. Most of the water produced with oil and gas operations in the WBRB has been managed by discharge under the WDEQ WYPDES program.

Groundwater withdrawal associated with uranium mining includes dewatering to facilitate surface and underground mining and filling open pits after surface mining and associated dewatering operations have ceased. Water may be discharged to the surface, and some is consumptively lost to evaporation and transpiration. Currently there is no active uranium mining in the WBRB. Future uranium mining will likely include in-situ recovery (ISR), which entails continuously circulating water through a mineralized zone and reclaiming the groundwater after mining has ceased. In the ISR process most groundwater ultimately remains in the aquifer, with approximately 1 percent withdrawn to maintain negative formation pressure. The withdrawn water is treated, and a minimal brine byproduct (approximately 0.01 percent) injected into deeper formations of equal or lower quality.

Surface and underground coal mining operations withdraw and manage groundwater in much the same way as does uranium mining. There is currently one semi-active coal mining operation in the WBRB, in the Grass Creek area. Future development of coal gasification resources could also cause groundwater withdrawals.

Groundwater produced as a byproduct of or integral with energy development is mostly put to other (non-consumptive) uses. A smaller volume is consumptively removed from the overall circulation system either by evaporation, transpiration, or injection into geologic units at a depth where there is little or no chance of future withdrawal. Because most conventional and CBNG produced water probably would not have been withdrawn for any other uses, and because most has been discharged to the surface, the overall effect of energy development has been to increase surface flows and the growth of vegetation. When produced water is injected it is effectively removed from consideration as a useable resource and could, therefore, be considered consumptively used.

8.3.5.4.2 Groundwater use for non-energy minerals development

Groundwater withdrawal for non-energy minerals development in the WBRB is primarily for bentonite and gypsum mining (MWH et al., 2010b); however, specific volumes were not available. **Figures 5-7, 5-8, and 5-9** show the locations of permitted, abandoned, and WSGS-mapped mine sites in the WBRB.

8.3.5.5 Irrigation-use permits (Figure 8-6)

Tables 8-6 and 8-7 list **459** groundwater permits for irrigation use as of June 2009, including one TWE permit. No permits for irrigation from the MBMG are included.

Figure 8-6 shows the distribution of irrigation permits in the WBRB, permits issued before and after 2000, and TWE permits. Most irrigation wells are located in rural areas and along rivers and other surface drainages where Quaternary and Tertiary hydrogeologic units can provide adequate groundwater for this high-volume use. The depth vs. yield tables on **Figure 8-6** show that while permits have been issued for all depth categories, most groundwater permits are for depths of 50 feet or less or for more than 1000 feet, across a wide range of yields for both total permits and permits issued since 2000. For permits since 2000, most permitted yields have been for 500 gpm or less. More than half of the irrigation-use permits are coded or have no recorded depth; **8** have coded yield information. TWE permits do not include depth data.

8.3.5.6 Livestock-stock use permits (Figure 8-7)

Tables 8-6, 8-7, and 8-8 show that the number of groundwater permits for stock use is exceeded only by the number of domestic-use permits in the WBRB, with **5,796** WSEO permits, **42** TWE permits, and **6** MBMG permits.

Figure 8-7 shows the distribution of stock permits in the WBRB, permits issued before and after 2000, and TWE permits. Stock wells are located throughout the WBRB, including rural areas of the WBRB where groundwater is the sole reliable source of water. The distribution of stock permits shows a strong correlation with rivers and other surface drainages within the interior basins; most are completed in Quaternary and Tertiary hydrogeologic units. Many permited wells (primarily permits issued before 2000) are also located in the areas between larger drainages and along the uplands of the basins, and are completed in various hydrogeologic units ranging from Quaternary to Precambrian and including both aquifers and confining units. The depth vs. yield tables on **Figure 8-7** show that by far the most groundwater permits are for depths of 500 feet or less and yields to 25 gpm for both total permits and permits since 2000. More than one-third of the permits for stock watering are coded or have no recorded depth (none of the TWE permits data include depth); **18** have coded yield information. **Figure 8-7** also shows that, like wells permitted for domestic use, stock wells have been mostly permitted at relatively shallow depth within virtually all

hydrogeologic units (including confining units) across a wide range of elevations within the WBRB, illustrating that useful quantities of relatively shallow groundwater can be found at most locations.

8.3.5.7 Miscellaneous-use permits (Figure 8-8)

Tables 8-6 and 8-7 list **1,755** groundwater permits for miscellaneous use in the WBRB as of June 2009, including **one** from the TWE data. No permits for miscellaneous use were available from the MBMG for the Montana BRB. Information on specific miscellaneous uses can be found in some cases in the permit applications. Some of these are available on-line; however, developing this information was beyond the scope of this study.

Figure 8-8 shows the distribution of permits permitted for miscellaneous use in the WBRB, permits issued before and after 2000, and TWE permits. Miscellaneous-use wells are located throughout the WBRB in population centers, in mineral development areas, in rural areas, and generally along rivers and larger surface drainages. The depth vs. yield tables on **Figure 8-8** show that while numerous permits have been issued for all depth and yield categories, the largest number of groundwater permits were issued for depths of 0 to 50 feet and 100 to 500 feet and for yields of 0 to 25 gpm for both total permits and permits issued since 2000. More than one-quarter of all permits for miscellaneous use have been issued since 2000. More than one-third of the miscellaneous-use permits are coded or have no recorded depth. None of the TWE permits data include depth; five have coded yield information.

8.3.5.8 Monitoring wells (Figure 8-9)

Tables 8-6 and 8-7 list **1,914** groundwater permits for monitoring wells in the WBRB, of which **one** is a MBMG permit for the Montana BRB. A monitoring well is typically used to monitor the level and quality of groundwater associated with a contaminated site or a potentially contaminated site (e.g., underground fuel storage tank) or to monitor for groundwater impacts from various activities (e.g., mining, waste management). When used for monitoring alone, these wells have no permitted yield; however, there may be a permitted yield for other uses. The WSEO required permits for monitoring wells of 4 inches or less in diameter only through 2004; therefore, the data for these permits is incomplete, possibly for other reasons as well (e.g., WSEO data-transfer problems).

Figure 8-9 shows the distribution of WSEO and MBMG monitoring well permits in the WBRB and permits issued before and after 2000. Most monitoring wells are located near population centers and along rivers and other large surface drainages, because that is where facilities that require groundwater monitoring are concentrated. The depth vs. yield tables on **Figure 8-9** show that while permits have been issued for all depth categories, by far the largest number were issued for depths of 0 to 50 feet and for yields of 0 to 25 gpm, for both total permits and permits since 2000, reflecting monitoring of the shallow water-table aquifers that are most susceptible to contamination. It is likely that most of these permits were issued for a yield of 0 gpm. One quarter of permits in the database for monitoring wells have been issued since 2000; and, as discussed above, this number is probably understated, per the 2004 WSEO policy change. Twenty percent of the monitoring-well permits are coded or have no recorded depth.

8.3.5.9 Other wells, test wells, and TWE commercial permits (Figure 8-10)

Table 8-6 lists **97** groundwater permits for test wells (TST) in the WBRB used for aquifer testing to determine aquifer characteristics. **Tables 8-6, 8-7, and 8-8** also list **54** "other" permits, for which a use was not identified, including **2** TWE and **2** MBMG permits, and **2** TWE Commercial (COM) permits.

Figure 8-10 shows the distribution of groundwater permits for test, "other," and TWE-commercial uses in the WBRB, and for total permits and permits issued after 2000. For both total permits and permits issued since 2000, the depth vs. yield tables on **Figure 8-10** show that depths range to greater than 1000 feet and most permitted yields are for 25 gpm or less.

8.3.5.10 Hydrothermal use

As described in **Section 4.7.3**, low-grade geothermal resources have been developed in the Thermopolis and Cody areas, and these and other areas in the WBRB have potential for additional development for commercial recreational and therapeutic uses. **Figure 4-1** shows areas of anomalously high heat flow that may provide opportunities for developing hydrothermal resources. The WSEO database does not include hydrothermal development as a primary use category, but in some cases it may be identified as a sub-category within the miscellaneous use (MIS) category in individual permit applications. Determination of the number of wells and springs permitted for hydrothermal use was beyond the scope of this study. The WBRB has limited potential for high-grade geothermal energy development near Yellowstone Park, but development of these resources will probably be restricted for a variety of reasons. Of course, there has been substantial development of hydrothermal resources for tourism in Yellowstone Park. Hinkley and Heasler (1987), and Heasler and Hinkley (1985) provide detailed discussions of the hydrothermal resources of the Wind River and Bighorn River Basins.

8.4 Groundwater interference/interconnection with surface water

The potential for interference between wells and well fields, particularly associated with areas of high drawdown over initial conditions, and interconnection between groundwater and

surface water should be considered when assessing the historic, current, and future use of groundwater. In general, when these issues arise they are addressed within the state's institutional and regulatory framework for groundwater development **(Chapter 1)**.

8.4.1 Interference between wells and drawdown

An objective of the previous groundwater Technical Memorandum (Lidstone and Associates, 2003) was to assess drawdown and potential well interference in two areas of intensive groundwater development near Riverton and Hyattville, in order to provide information on whether establishment of groundwater control areas should be considered for either area. Near Riverton the Wind River aquifer has been extensively developed, primarily for municipal and domestic use. In the vicinity of Ten Sleep and Hyattville, the Tensleep, Madison–Bighorn, and Flathead aquifers have been developed for agricultural, municipal, and industrial uses.

According to Wyoming statutes, a control area can be designated by the Board of Control per recommendation of the State Engineer for any of the following reasons:

- The use of underground water is approaching a use equal to the current recharge rate
- Groundwater levels are declining or have declined extensively
- Conflicts between users are occurring or are foreseeable
- The waste of water is occurring or may occur
- Other conditions exist or may arise that require regulation for the protection of the public interest

Lidstone and Associates (2003) found that the groundwater level and wellhead pressure have declined substantially as a result of withdrawal in both the Riverton and Tensleep/Hyattville areas. On the basis of persistent decline in both areas, Lidstone and Associates (2003) and WWC Engineering et al. (2007b) recommended that the WSEO develop additional information and consider whether establishing control areas is warranted. To date no control areas have been established in the WBRB (Lisa Lindemann, WSEO, 2009, pers. comm.).

8.4.2 Interconnection between groundwater and surface water

Surface flows are generally subject to strict water rights, and conflicts could occur where groundwater extraction affects surface flow. In general, the deeper and more distant an aquifer is from surface water, the less potential there is for interconnection with surface water. The potential for stream depletion due to interconnection between groundwater and surface water is highest where alluvial aquifers are associated with active streams **(Sections 5.1.3 and 6.2, Chapter 7)** and in areas around the perimeters of the basins where rejected recharge provides substantial surface flows **(Section 5.1.3 and 5.4)**.

Groundwater drain systems, installed as irrigation was developed in the basins, provide another interconnection among shallow alluvial aquifer groundwater, streams, and canals. The shallow drains were installed over several decades to alleviate persistent saturated soil conditions and associated salt deposition within irrigated areas. It can be argued that the interconnection between groundwater and surface water via these drains is redundant because the drains only speed irrigation return flows (and in some cases redirect them, for example to a canal rather than a natural stream) and have little or no relation to surface-water depletion. For this study the possibility of mapping the drain systems was briefly investigated. While some mapping exists, it is dated, possibly incomplete, not widely available, dispersed in older government reports and Bureau of Reclamation files, and in the possession of many seperate irrigation districts (26 in the WBRB), individual irrigators, and possibly others. Comprehensive mapping of these systems (or only their discharge points) is beyond the scope of this study, but may be a worthwhile component of a future update of this memorandum. For example, locating and sampling the discharge points for these drain systems might provide useful spatially-averaged samples of the shallow groundwater quality of local irrigated areas.

Currently, no statewide criteria have been established for assessing the interconnection between groundwater and surface water in Wyoming. Neither have estimates been developed for "not connected" groundwater volumes. However, the Modified "*North Platte Decree*" defines "hydrological connection" as a stream depletion of 28 percent or more of the volume pumped over 40 years. In other states, depletion has been defined as 10 percent in 50 years, 1 percent in 100 years, etc. A copy of the *Decree* can be found at

> http://seo.state.wy.us/PDF/Nebreska v.Wyoming – Modified North Platte Decree.pdf

Chapter 9

Looking to the Future

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Scott Quillinan

Chapter 1, Part 2 introduces the groundwater regime of the WBRB and gives an overview of future development prospects. Elements of specific groundwater development potential are discussed below in Section 9.1, and recommendations for future updates of this Available Groundwater Determination Technical Memorandum in Section 9.2.

9.1 Future groundwater development

The prospects for future development of specific groundwater resources in the WBRB are described in this section using information developed for this study:

- Hydrogeology **(Chapters 5, 6, and 7)**
- Current and historic development patterns based on groundwater permitting information **(Chapter 8)**
- Development potential of specific aquifers based on information compiled from previous studies **(Chapter 7)**
- Specific potential groundwater development projects identified in the 2003 Water Plan for the WBRB (BRS, Inc. et al., 2003), the 2007 State Water Plan (WWC Engineering et al., 2007b), and the current (2010) Update Plan (MWH et al., 2010a) and their associated Technical Memoranda

Only development of fresh groundwater for supply purposes is addressed in this chapter. The development potential of groundwater produced as a byproduct of industrial activities (e.g. oil and gas operations) is not addressed.

9.1.1 Aquifer-specific development potential

Information concerning the potential for new or additional groundwater development of specific hydrogeologic units in the WBRB was compiled from a variety of sources for **Chapter 7** of this study. The development potential of specific units discussed in **Chapter 7** is summarized in **Appendix D**, along with a brief discussion of the various factors that affect the viability of developing groundwater resources in these units. Table 2 of the WWDC 2003 Available Ground Water Determination Technical Memorandum (Lidstone and Associates, 2003) provides similar tabulated aquifer-specific information.

Appendix B presents a summary, in chronological order, of all WWDC-sponsored studies relevant to groundwater development in the WBRB since 1982. Many of these studies were used in compiling the aquifer-specific information presented in **Chapter 7;** therefore, these data are also generally summarized in **Appendix D**. **Appendix B** summarizes the following information relevant to developing new or additional groundwater resources in the WBRB:

- References to the study(s) – full citations are included in the References
- Location, including as appropriate: town, county, rural area, irrigation district, well site, etc.
- Aquifers involved in the study
- Project descriptions:
    - Studies of development potential of area(s and aquifer(s)
    - Development drilling project(s)
    - Study results
- Project status

9.1.2 Aquifers and specific projects

Numerous hydrogeological investigations have been performed in the WBRB. Previous Water Plans (BRS, Inc. et al., 2003; WWC Engineering et al., 2007a) provide general conclusions regarding the groundwater development potential of the major aquifers of the WBRB, summarized below:

Virtually all aquifers and some confining units have some potential for development, depending on quantity and quality requirements and technical considerations.

Quaternary alluvial subaquifers have local development potential. Depending on local hydrogeologic conditions, well yields are expected to range from 10 to 500 gpm. Water quality and susceptibility to surface sources of contamination (e.g. irrigation) should be considered in evaluating development prospects.

The Lower Tertiary Wind River aquifer is developed in several areas in the Wind River Basin, especially in the vicinity of Riverton. Opportunities for additional groundwater development, including high-capacity wells, exist mostly in areas near major surface drainages, primarily the Wind River. Water quality may constrain development in some areas.

The Paleozoic aquifers, primarily the Madison–Bighorn aquifer in the Bighorn Basin (the Madison aquifer in the Wind River Basin), probably have the best potential for developing high-yield wells, depending on site-specific hydrogeologic conditions. Yields up to 14,000 gpm under flowing artesian conditions have been measured from the Madison–Bighorn along the west side of the Bighorn Basin. Because Paleozoic aquifers are confined in most places, lowered hydraulic head associated with large withdrawals, great drilling depth, and poor water quality may constrain development in some areas. Large variations in structure- and solution-controlled permeability will necessitate site-specific investigations to evaluate new development prospects.

The Flathead aquifer also has potential for developing high-yield wells, but is limited to areas where the sandstone formation can be accessed at economic depth, generally not far from outcrop. The Flathead is generally characterized by high artesian pressure, and it has produced large artesian flows

as great as 3,000 gpm. As with the Madison–Bighorn aquifer, drilling depth and water quality will constrain development in the WBRB.

Previous Water Plans (BRS, Inc. et al., 2003; WWC Engineering et al., 2007a) included lists of groundwater opportunities (by category), developed by the Wind/Bighorn Basin Planning Team (WWDC, other agencies, and consultants) and Basin Advisory Group (BAG) for use by individuals and organizations that will require some level of public support for groundwater development projects to meet specific existing and anticipated withdrawal requirements. The previous Water Plans discuss in detail the categories, screening criteria, and other considerations under which a "long list" of groundwater development opportunities was developed and evaluated to produce a "short list" of opportunities perceived to be most beneficial and feasible over a 30-year period, based on the screening criteria below:

1. Need – the capacity of a successful project to meet specific existing and anticipated water needs
2. Water availability – the likelihood that an aquifer can provide sustainable yield adequate to meet anticipated demand
3. Financial feasibility – the combined technical considerations and construction costs compared with the economic benefits of the project
4. Public acceptance – the degree to which the public supports or opposes the project
5. Number of sponsors/beneficiaries/participants – the beneficial aspects of a project relative to the population to be served
6. Legal/institutional concerns – the likelihood that a project would be authorized and permitted under applicable state and federal laws
7. Environmental/recreational benefits – the potential for a project to have a positive or negative impact on recreation or the environment (e.g., a groundwater project's potential for decreasing stream flows)

The previous WBRB Water Plans (BRS, Inc. et al., 2003; WWC Engineering et al., 2007a) also noted that because of treatment requirements for surface waters under the Safe Drinking Water Act and recent drought conditions, many municipalities and other public water supply systems are increasingly interested in developing groundwater resources.

The current 2010 Update Water Plan for the WBRB (MWH et. al, 2010a) presents an updated list of specific groundwater project opportunities to address existing and future use requirements based on the lists presented in the previous Water Plans, supplemented by studies completed since 2003 and additional recommendations from the BAG and the Basin Planning Team. The following potential groundwater projects from the 2010 Plan are presented to illustrate the prospects, some of which have been identified for several years, that reflect a general consensus on the foremost opportunities for new and additional public-support groundwater development in the WBRB.

- Flathead aquifer near Lander
- Paleozoic aquifers (Madison–Bighorn, Flathead) near Thermopolis and Hyattville
- Madison–Bighorn aquifer in the southern Bighorn Basin
- Shallow to deep aquifers in the upper Bighorn Basin
- Tensleep aquifer near Big Trails
- Paleozoic aquifers in the Mud Creek Basin
- Wind River aquifer in the Gas Hills area

As of late 2010, current and planned WWDC-funded groundwater projects the WBRB include (Keith Clarey, pers. comm., 2010):

- The **Arapahoe Water Supply Level II Study** (2006-2010) funded the construction of a test/production well with a depth of 1,041 feet and a yield of 300 gpm and other wells. A series of shallow test wells constructed into alluvial deposits along the Little Wind River were also evaluated for use as a back-up supply for the local Ethete public water system on the Wind River Indian Reservation. An alluvial well field system is planned to be connected to the Northern Arapahoe Utilities Organization public surface water system during the Level III construction project, 2010-2011.

- The **Bighorn Regional Groundwater Level II Study** (2005-2010) is a study for the Big Horn Regional Joint Powers Board (BHRJPB). The BHRJPB is supplied with groundwater from the City of Worland well field. Four deep test/production wells have been constructed to find a new well to serve as a redundant source of supply for the regional system. The fourth well is considered a potential production supply well for connection to the regional public water system.

- The **Pavillion Area Water Supply Level I Study** (Fall 2010) is a study to investigate a long-term alternative water supply for the rural residents living east of the Town of Pavillion to replace their contaminated private water wells. In August 2010, the USEPA Region 8 office issued an advisory to these Fremont County rural residents to not drink their private well water due to contamination by dissolved hydrocarbon and inorganic compounds.

9.1.3 Groundwater interference and interconnection with surface water

The potential for interference between wells or well fields and associated areas of high drawdown over initial conditions, and interconnections between groundwater and surface water, should be considered in assessing the potential for developing groundwater resources. These issues are discussed in **Section 8.4** and briefly in **Section 1.**

9.2 Recommendations for future updates

The Wyoming State Water Plan Available Groundwater Determinations for the WBRB (and other major drainage basins of Wyoming) are limited by the availability of data and the institutional resources that can be marshaled to compile and develop the information in a form that is accessible and useful to stakeholders in groundwater development. While some information (e.g., hydrogeology, WSEO groundwater permit, other agency data) is available for all basins, other information (e.g. regional groundwater modeling) may not exist. The quality, quantity, accuracy, and completeness of available groundwater information vary between and within the major drainage basins of Wyoming.

The purpose of updating an Available Groundwater Determination can be to include information generated since the previous determination, to include older information not initially provided, and to utilize our continuously improving technology to maximize the value of compiling, developing, and presenting the full body of relevant information. While some information will grow slowly (e.g., mapping of geologic and hydrogeologic units), other information will need to be continuously updated to maintain its utility (e.g., WSEO and other agency data).

9.2.1 Data Challenges

Computing capabilities will continuously improve but will always be limited by data availability and reliability. The quality of a study that relies substantially on data processing may, therefore, be substantially enhanced through improved data. Specific areas for data improvement in the WBRB include:

- WSEO and WDEQ database issues (**Appendix C**), primarily:
    - consistency between the various databases
    - accessibility of databases
    - definition of how current, complete, and accurate the information is; what information has been excluded, and why
    - the uniqueness of the data and the need for common identifiers to distinguish data duplicated in different databases
- development of a comprehensive database for water quality and aquifer physical characteristics.

Hydrogeologic and hydrogeochemical data exist that could be integrated into a more comprehensive and evolving groundwater database for Wyoming. For example, WDEQ collects copious groundwater information from site-specific investigations of contaminated sites, for issuing industrial permits (e.g. mining, UIC, waste and wastewater management), for monitoring for potential impacts, and other activities. The WSEO collects groundwater information from selected wells. The USGS, WOGCC, BLM, EPA, TWE, counties, municipalities, other agencies, and private entities all collect groundwater 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 the WBRB and other Available Groundwater Determinations. While the quality of some of this information may not be consistent with the standards described in **Chapter 7**, those data could be qualified. In addition, 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 updating and maintenance of a comprehensive groundwater information database where data are being generated by several entities would be a substantial project, requiring a continuing commitment of resources by Federal, State, and local agencies – and is likely easier described than done. As interest in groundwater resources increases, so will justification for such a program.

9.2.2 Future Efforts

This study is substantially more comprehensive than the previous groundwater determination. For the most part, no original investigations were performed for this study; however, additional information is summarized to the extent that significant advancement of the conceptual model of WBRB groundwater resources would require original efforts on a basin-wide scale. Ideally, numeric modeling of aquifer performance and three-dimensional models of groundwater basin geology and hydrogeology including the areal extent, thickness, continuity, structure, hydraulic characteristics, groundwater quality, and total and available groundwater resources of the hydrogeologic unit components of the WBRB would be the basis of better definition of the groundwater resource. Developing numeric and 3-D models of the groundwater basin would require extensive subsurface data collection and processing.

The **Section 6.2** evaluation of groundwater volume and recharge based on the surface outcrop area of hydrogeologic units and the SDVC map of recharge (Hamerlinck and Arneson, 1998) went beyond summarizing existing information by using the data for estimating the groundwater resource. The evaluation

of recharge implemented 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 could be enhanced by updated numeric modeling that includes the additional variables that affect infiltration and recharge (**Section 5.1.3**).

Other areas where useful information could be developed for the Available Groundwater Determination for the WBRB include:

- more detailed geologic mapping to better define the function of hydrogeologic units as aquifers or confining units based on lithology, stratigraphic position, and structural relationships

- priority ranking of areas where numerical modeling would be most useful

- identification of any additional areas where interference between wells and well fields should be considered in evaluating future groundwater development

- identification of areas where groundwater and surface water may be interconnected

- inclusion on the surface hydrogeology map (**Plate IV**) of shallow anticlinal axes that may affect groundwater flow

- mapping linear segments of surface-water drainages, primarily where Tertiary geologic units are exposed or thinly covered by Quaternary deposits in the basin interiors, to identify areas where vertical recharge may be enhanced by fracture permeability

- mapping irrigation drain systems and sampling the discharge points to provide spatially-averaged water quality of the shallowest groundwater in local irrigated areas

- mapping areas covered by WWDC studies listed in **Appendix B**

- developing an on-line site where stakeholders can submit information and comments relevant to the Available Groundwater Determination

- developing additional and specific information on institutional, legal, and cultural issues that could affect groundwater development in the WBRB

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Appendices

Appendix A

Description of GIS Geologic Units, Wind/Bighorn River Basin, Wyoming

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Appendix A. Description of GIS Geologic Units, Wind/Bighorn River Basin, Wyoming and Montana

Compiled by
Keith Clarey, Nik Gribb, Brett Worman, and Scott Quillinan

This appendix describes the 83 Geographic Information System (GIS) geologic units that compose the Wind/Bighorn River Basin of Wyoming and Montana. The lithostratigraphic descriptions in this appendix are for the geologic units shown on **Plate I**. Of the 84 geologic units, 34 are present in both Wyoming and Montana and are denoted with by an asterisk after the lithostratigraphic description.

These geologic units are compiled from those parts of the two 1:500,000-scale digital state maps that cover the WBRB. Each map gives a code and rock-type description for each unit within the mapped state: each state has its own set of codes, and neither codes nor unit boundaries necessarily match across the state border. We have therefore modified the Montana geologic unit names to match their Wyoming geologic unit equivalents.

In this appendix each GIS code and rock-type citation in italics is followed by a description of the corresponding lithostratigraphic unit(s) as defined in Wyoming. **Plate V** summarizes these determinations. The abbreviation "Ma" denotes "mega annum" or "million years before present." lithostratigraphic units that appear in the left-hand column of **Plates II and III** are in **boldface**.

WIND/BIGHORN BASIN GEOLOGIC UNITS – WYOMING AND MONTANA

There are 117 digital GIS geologic units in the Wind/Bighorn River Basin, including surface water and ice units, and combining all Precambrian units into a single unit called Precambrian rocks (p€r). The stratigraphic descriptions below are taken directly from Love and Christiansen (1985) with minor modifications.

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Unit Symbol	***Unit Description***
CENOZOIC GEOLOGIC UNITS - Wyoming	
Quaternary geologic units - Wyoming	
Water	*Water* [surface water].*
Ice	*Ice* [glacial ice, only mapped in the Wind River Range in the WBRB.]

Qa *Quaternary: Pleistocene-Holocene: alluvium and colluvium deposits.**
Alluvium and colluvium (Qa) (Pleistocene to Holocene) – Clay, silt, sand, and gravel present in flood plains, fans, terraces, and slopes (Love and Christiansen, 1985).

Qg *Quaternary: Pleistocene-Holocene: glacial drift deposits.**
Glacial deposits (Qg) (Pleistocene to Holocene) – Till and outwash of sand, gravel, and boulders (Love and Christiansen, 1985).

Ql *Quaternary: Pleistocene-Holocene: playa lake or marine deposits (non-glacial).*
Playa lake and other lacustrine deposits (Ql) (Pleistocene to Holocene) – Chiefly clay, silt, and fine sand. Includes travertine deposits (Love and Christiansen, 1985).

Qls *Quaternary: Pleistocene-Holocene: landslide and glacial drift deposits.*
Landslide deposits (Qls) (Pleistocene to Holocene) – Local intermixed landslide and glacial deposits, talus, and rock-glacier deposits (Love and Christiansen, 1985).

Qs *Quaternary: Pleistocene-Holocene: dune sand and loess deposits (eolian deposits).*
Dune sand and loess (Qs) (Pleistocene to Holocene) – Includes active and dormant sand dunes and in northwestern Wyoming is chiefly loess (12,000-19,000 years old) (Love and Christiansen, 1985).

Qt *Quaternary: Pleistocene-Holocene: unconsolidated deposits.**
Gravel, pediment, and fan deposits (Qt) (Pleistocene to Holocene) – Mostly locally derived clasts; includes some glacial deposits along flanks of Wind River Range; and locally may include some Tertiary gravels (Love and Christiansen, 1985). [Exposed along the northeastern to eastern flank of the Wind River Range in the Wind River Basin.]

Qu *Quaternary: Pleistocene-Holocene: alluvium and colluvium deposits.**
Undivided surficial deposits (Qu) (Pleistocene to Holocene) – Mostly alluvium, colluvium, and glacial and landslide deposits (Love and Christiansen, 1985).

Qb *Quaternary: Pleistocene-Holocene: basalt rocks.*
Basalt flows, tuff, and intrusive igneous rocks (Qb) (Pleistocene)

Basalt flows and intrusive igneous rocks (Qb) – Yellowstone area – Unit includes Osprey, Madison River, Swan Lake Flat, and Falls River Basalts, basalts of Mariposa Lake, Undine Falls Basalt, and gravels, sands, silts, and basalts of The Narrows (Love and Christiansen, 1985). [Exposed in the Yellowstone area of northwestern Wyoming.]

Basalt flows and intrusive igneous rocks (Qb) – In and adjacent to Absaroka and Washakie Ranges – Includes basalt of Lava Mountain (~0.5 Ma) (Love and Christiansen, 1985). [Exposed in Absaroka Range and Washakie Range of northwestern Wyoming.]

Qr *Quaternary: Pleistocene-Holocene: rhyolite and lava flow rocks.*
Rhyolite flows, tuff, and intrusive igneous rocks (Qr) (Pleistocene) – Includes Plateau Rhyolite (~0.07 Ma) and interlayered sediments, Mount Jackson Rhyolite (0.6 to ~1.0 Ma), Lewis Canyon Rhyolite (~0.9 Ma), and Lava Creek Tuff of Yellowstone Group (0.6 to ~1.0 Ma) (Love and Christiansen, 1985). [Exposed in northwestern Wyoming.]

QTg *Tertiary-Quaternary: Pliocene-Pleistocene: gravel deposits.*
Terrace gravel (QTg) (Pliocene(?) to Pleistocene) – Partly consolidated gravel above and flanking some major streams (Love and Christiansen, 1985).

Upper Tertiary geologic units – Wyoming

Thr *Tertiary: Pliocene: rhyolite and tuff rocks.**
Huckleberry Ridge Tuff of Yellowstone Group (Thr) (Pliocene) – Lavender to gray-brown welded rhyolite tuff (Love and Christiansen, 1985). [Exposed in the Yellowstone area of northwestern Wyoming.]

Tii *Tertiary: Miocene-Pliocene: granitoid and basalt rocks.*
Intrusive and extrusive igneous rocks (Tii) (Miocene to Pliocene) – Igneous rocks, in composition from hornblende monzonite to basalt; in Yellowstone area includes andesite and basalt of Emerald Lake (~2 Ma), rhyolite of Broad Creek, Pliocene Junction Butte Basalt, and gravel of Mount Evans. Age of basalt on Crescent Mountain 3.6 Ma (Love and Christiansen, 1985). [Northwestern Wyoming] [Tertiary]

Tcv *Tertiary: Miocene-Pliocene: dacite and felsic volcanic rocks.*
Caldwell Canyon Volcanics (Tcv) (Miocene to Pliocene) – Southern Absaroka Range – Includes dacitic volcanic rocks and obsidian gravel at base (Love and Christiansen, 1985). [Exposed in the southern Absaroka Range.]

Tmu *Tertiary: Upper Miocene: sandstone and claystone.*
Upper Miocene rocks (undivided) (Tmu) (Upper Miocene)

Upper Miocene rocks (Tmu) – South end of Wind River Mountains – Siliceous, arkosic, and locally radioactive sandstone, claystone, and conglomerate. Fission-track age ~27 Ma. Recent work suggests that part of these deposits may be of Eocene age. These rocks were originally defined as the Miocene-Pliocene **South Pass Formation** (Love and Christiansen, 1985). [Exposed only in the South Pass area at the southern end of the Wind River Range.]

Upper Miocene rocks (Tmu) – Central Wyoming – Arkosic sandstone, conglomerate, and siltstone; some light-colored tuffaceous radioactive claystone and white cherty limestone (Tmu) (Love and Christiansen, 1985).

Upper Miocene rocks (Tmu) – Central Wyoming: North of Sweetwater River in Granite Mountains – Light-colored tuffaceous radioactive claystone, siltstone, sandstone, and arkose; Moonstone Formation (Tmu) (Love and Christiansen, 1985).

Tm *Tertiary: Miocene: sandstone and conglomerate.*
Miocene rocks (undivided) (Tm) (Miocene)

Miocene rocks (Tm) – Central Wyoming – White soft tuffaceous sandstone; locally derived conglomerate in upper and lower parts of sequence; in places lower conglomeratic sequence may be of Oligocene age. In Granite Mountains K/Ar age of tuff in lower part of sandstone sequence ~17 Ma and fission-track age of lower conglomerate ~24 Ma (Love and Christiansen, 1985).

Miocene rocks (Tm) – South Pass area at southern end of the Wind River Range – White soft tuffaceous sandstone; locally derived conglomerate in upper and lower parts of sequence; in places lower conglomeratic sequence may be of Oligocene age (Love and Christiansen, 1985).

Tml *Tertiary: Lower Miocene: sandstone.*
Lower Miocene rocks (undivided) (Tml) (Lower Miocene)

Lower Miocene rocks (Tml) – Northwest Wyoming (Bighorn Mountain) – Gray, soft, poorly bedded to massive sandstone (Love and Christiansen, 1985).

Lower Miocene rocks (Tml) – Central Wyoming – Tuffaceous sandstone, siltstone, and white marl (Love and Christiansen, 1985).

Lower Tertiary geologic units – Wyoming

Twr *Tertiary: Oligocene: fine-grained mixed clastic and medium-grained mixed clastic rocks.*
White River Formation (Twr) (Oligocene; 31-35 Ma) – White to pale-pink blocky tuffaceous claystone and lenticular arkosic conglomerate (Love and Christiansen, 1985).

Ti *Tertiary: Eocene: plutonic rocks.**
Intrusive igneous rocks (Ti) (Eocene) – Felsic and mafic plutonic igneous bodies, the larger ones dominantly felsic (Love and Christiansen, 1985). [Exposed in northwestern Wyoming.]

Tts *Tertiary: Eocene: andesite and pyroclastic rocks.**
Thorofare Creek Group of the Absaroka Volcanic Supergroup – intrusive igneous rocks (Tts) (Eocene; 47-48 Ma) – Dark-colored andesitic volcaniclastic rocks and flows underlain by light-colored andesitic tuffs and flows; in places may include Trout Peak Trachyandesite of Sunlight Group (Love and Christiansen, 1985). [Exposed in northwestern Wyoming.]

Twi *Tertiary: Eocene: mixed clastic/volcanic rocks.*
Wiggins Formation of the Thorofare Creek Group (Twi) (Eocene; 44-47 Ma) – Light-gray volcanic conglomerate and white tuff, containing clasts of igneous rocks (Love and Christiansen, 1985).

Ttl *Tertiary: Eocene: mixed clastic/volcanic and intermediate volcanic rocks.*
Two Ocean and Langford Formations of the Thorofare Creek Group (Ttl, Tts) (Eocene; 47-48 Ma) – Dark-colored andesitic volcaniclastic rocks and flows underlain by light-colored andesitic tuffs and flows (Love and Christiansen, 1985).

Tt *Tertiary: Eocene: mixed clastic/volcanic and medium-grained mixed clastic rocks.*

Tepee Trail Formation of the Thorofare Creek Group (Tt) (Eocene; ~48 Ma) – Green and olive-drab hard generally well bedded andesitic conglomerate, sandstone, and claystone (Love and Christiansen, 1985).

Ta *Tertiary: Eocene: mixed clastic/volcanic and fine-grained mixed clastic rocks.*

Aycross Formation of the Thorofare Creek Group (Ta) (Eocene; 49 Ma) – 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 (Love and Christiansen, 1985).

Ts *Tertiary: Eocene: intermediate volcanic and basalt rocks.**

Sunlight Group of the Absaroka Volcanic Supergroup (Ts) (Eocene) [Exposed in northwestern Wyoming.]

Ttp *Tertiary: Eocene: trachyandesite rocks.*

Trout Peak Trachyandesite of the Sunlight Group (Ttp) (Eocene)

Twp *Tertiary: Eocene: mixed clastic/volcanic and intermediate volcanic rocks.**

Wapiti Formation of the Sunlight Group (Twp) (Eocene) – Andesitic volcaniclastic rocks (Love and Christiansen, 1985).

Ts *Tertiary: Eocene:intermediate volcanic and basalt rocks.*

Cresent Hill Basalt (Ts)

Mount Wallace Formation (Ts) – Felsic and mafic volcaniclastic rocks (Love and Christiansen, 1985).

Taw *Tertiary: Eocene: mixed clastic/volcanic and intermediate volcanic rocks.**

Washburn Group of the Absaroka Volcanic Supergroup (Taw) (Eocene) [Exposed in northwestern Wyoming.]

Sepulcher Formation of the Washburn Group (Taw) – Andesitic and dacitic volcaniclastic rocks (Love and Christiansen, 1985).

Lamar River Formation of the Washburn Group (Taw) – Andesitic lava and volcaniclastic rocks (Love and Christiansen, 1985).

Cathedral Cliffs Formation of the Washburn Group (Taw) – Light-colored andesitic volcaniclastic rocks (Love and Christiansen, 1985).

Twb *Tertiary: Eocene: claystone and conglomerate.*

Wagon Bed Formation (Twb) (Eocene; ~45-49 Ma) – Southwest and central Wyoming – Green and gray tuffaceous claystone, sandstone, and conglomerate; some uranium-phosphate marlstone and variegated bentonitic claystone; locally contains oil shale between Wind River and Bighorn Basins (Love and Christiansen, 1985).

Tv *Tertiary: Eocene: conglomerate and mixed clastic/volcanic rocks.*

Volcanic conglomerate (Tv) (Eocene) – Jackson Hole – Dark-brown to black conglomerate, poorly bedded, composed chiefly of basalt clasts in a basaltic tuff matrix (Love and Christiansen, 1985). [Exposed in the Jackson Hole area of Teton County.]

Tcr *Tertiary: Eocene: conglomerate.*

Crandall Conglomerate (Tcr) (Lower Eocene) – East flank of Absaroka Range – Composed of non-volcanic conglomerate containing clasts of Lower Paleozoic rocks (Love and Christiansen, 1985).

Twdr *Tertiary: Eocene: claystone and siltstone.*

Wind River Formation (Twdr) (Eocene) [Exposed in central and northwestern Wyoming.]

Wind River Formation (Twdr) – Northwest Wyoming (Jackson Hole) – Variegated red and white claystone and siltstone; largely non-tuffaceous except near the top; lenticular coal unit in middle; at base locally includes equivalent of **Indian Meadows Formation** (Love and Christiansen, 1985).

Wind River Formation (Twdr) – Central Wyoming – Variegated claystone and sandstone; lenticular conglomerate. Age of tuff at top 49 Ma (Love and Christiansen, 1985).

Twim *Tertiary: Eocene: fine-grained mixed clastic and medium-grained mixed clastic rocks.*

Wind River and Indian Meadows Formations (undivided) (Twim) (Eocene) – This unit is mapped as a combined unit and includes portions of the following two formations in central Wyoming:

Wind River Formation (Twim) – Variegated claystone and sandstone; lenticular conglomerate; age of tuff at top 49 Ma (Love and Christiansen, 1985); and

Indian Meadows Formation (Twim) – Red to variegated claystone, sandstone, and algal-ball limestone; some beds of large Paleozoic boulders and detachment masses of Paleozoic and Mesozoic rocks (Love and Christiansen, 1985).

Tim *Tertiary: Eocene: fine-grained mixed clastic and medium-grained mixed clastic rocks.*
Indian Meadows Formation (Tim) (Eocene) – Red to variegated claystone, sandstone, and algal-ball limestone; some beds of large Paleozoic boulders and detachment masses of Paleozoic and Mesozoic rocks (Love and Christiansen, 1985). [Exposed in central Wyoming.]

Tta *Tertiary: Eocene: fine-grained mixed clastic and oil shale rocks.*
Tatman Formation (Tta) (Eocene) – Drab non-tuffaceous claystone, oil shale, lignite, and sandstone (Love and Christiansen, 1985). [Exposed in northwestern Wyoming.]

Twl *Tertiary: Eocene: fine-grained mixed clastic and medium-grained mixed clastic rocks.**
Willwood Formation (Twl) (Eocene) – Composed of variegated claystone, shale, and sandstone; including some lenticular gold-bearing quartzite conglomerate (Love and Christiansen, 1985). [Exposed in the Bighorn Basin of northwestern Wyoming.]

Tfu *Tertiary: Paleocene: sandstone and shale.**
Fort Union Formation (Tfu) (Paleocene) – Brown to gray sandstone, gray to black shale, and thin coal beds (Love and Christiansen, 1985). [Exposed in central and northwestern Wyoming.]

TKu *Upper Cretaceous-Paleocene: sandstone and shale.*
Sedimentary rocks (TKu) (Upper Cretaceous to Paleocene) – White-weathering oil-stained sandstone and brown carbonaceous shale (Love and Christiansen, 1985). [Exposed only in the northern Wind River Basin in northeastern Fremont County and northwestern Natrona County.]

MESOZOIC GEOLOGIC UNITS - Wyoming

Upper Cretaceous geologic units - Wyoming

Ki *Lower to Upper Cretaceous (?): plutonic rocks.*
Intrusive igneous rocks (Ki) (Lower to Upper Cretaceous (?)) – Gray to buff, monzonite porphyry (Love and Christiansen, 1985).

Klc *Upper Cretaceous: sandstone and conglomerate.*
Landslide Creek Formation (Klc) (Upper Cretaceous) – Green-gray, bentonitic, tuffaceous, interbedded sandstone and conglomerate (Love and Christiansen, 1985). [Exposed in the northern Yellowstone area of Wyoming.]

Kha *Upper Cretaceous: conglomerate and sandstone.*
Harebell Formation (Kha) (Upper Cretaceous) – Gold-bearing quartzite conglomerate interbedded with olive-drab sandstone and green claystone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Kl *Upper Cretaceous: sandstone and shale.**
Lance Formation (Kl) (Upper Cretaceous) – North Wyoming – Thick-bedded buff sandstone and drab to green shale; interbedded with thin conglomerate lenses (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Klm *Upper Cretaceous: medium-grained mixed clastic and fine-grained mixed clastic rocks.*
Lance Formation, Fox Hills Sandstone, **Meeteetse Formation**, Bearpaw Shale, and **Lewis Shale** (Klm) (Upper Cretaceous) – This combined GIS geologic unit in the Bighorn Basin consists of the Lance and Meeteetse Formations, and, in the southeastern part, includes a tongue of Lewis Shale (Love and Christiansen, 1985). In the northern Wind River Basin, it is composed of the Lance Formation, Meeteetse Formation, and Lewis Shale; and in the southeastern basin, the Lance Formation and Lewis Shale (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Lance Formation (Klm) – North Wyoming – Thick-bedded buff sandstone and drab to green shale; interbedded with thin conglomerate lenses (Love and Christiansen, 1985).
Fox Hills Sandstone (Klm) – Light-colored sandstone and gray sandy shale containing marine fossils (Love and Christiansen, 1985).
Meeteetse Formation (Klm) – Chalky-white to gray sandstone; yellow, green, and dark-gray bentonitic claystone; white tuff; and thin coal beds (Love and Christiansen, 1985).
Bearpaw Shale (Klm) – Dark-greenish-gray shale containing thin gray sandstone partings (Love and Christiansen, 1985).
Lewis Shale (Klm) – Gray marine shale containing abundant interbedded gray and brown, lenticular,

concretion-rich sandstone beds (Love and Christiansen, 1985).

Km *Upper Cretaceous: sandstone and claystone.**
Meeteetse Formation (Km) (Upper Cretaceous; ~73 Ma) – Chalky-white to gray sandstone; yellow, green, and dark-gray bentonitic claystone; white tuff; and thin coal beds (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Kml *Upper Cretaceous: medium-grained mixed clastic and fine-grained mixed clastic rocks.*
Meeteetse Formation and Lewis Shale (Kml) (Upper Cretaceous) [Exposed in northern Wyoming.]
Meeteetse Formation (Kml) – Chalky-white to gray sandstone; yellow, green, and dark-gray bentonitic claystone; white tuff; and thin coal beds (Love and Christiansen, 1985).
Lewis Shale (Kml) – Gray marine shale containing many gray and brown lenticular concretion-rich sandstone beds (Love and Christiansen, 1985).

Kle *Upper Cretaceous: shale and sandstone.*
Lewis Shale (Kle) (Upper Cretaceous; ~68 Ma) – Gray marine shale containing abundant interbedded gray and brown lenticular concretion-rich sandstone beds (Love and Christiansen, 1985). [Exposed in the northern Wyoming.]

Ket *Upper Cretaceous: sandstone and mudstone.*
Everts Formation, **Eagle Sandstone**, and Telegraph Creek Formation (Ket) (Upper Cretaceous) – Combined stratigraphic unit – Massive to thin-bedded sandstone, mudstone, and shale (Love and Christiansen, 1985). [Exposed in the northern Yellowstone area of Wyoming.]

Kb *Upper Cretaceous: sandstone and coal.*
Bacon Ridge Sandstone (Kb) (Upper Cretaceous) – Gray to tan marine sandstone and thick coal beds; gold-bearing quartzite conglomerate in lower part (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Kmv *Upper Cretaceous: sandstone and shale.**
Mesaverde Formation (Kmv) (Upper Cretaceous) – Light-colored massive to thin-bedded sandstone, gray sandy shale, and coal beds; in Jackson Hole, the unit locally contains gold-bearing quartzite conglomerate (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Kc *Upper Cretaceous: shale and siltstone.**
Cody Shale (Kc) (Upper Cretaceous; 78-83 Ma) – Northern Yellowstone area – Gray to brown shale and siltstone (Love and Christiansen, 1985). [Exposed in the northern Yellowstone area of Wyoming.]
Cody Shale (Kc) (Upper Cretaceous; 78-83 Ma) – Northern Wyoming – Dull-gray shale, gray siltstone, and fine-grained gray sandstone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Kf *Upper Cretaceous: sandstone and shale.**
Frontier Formation (Kf) (Upper Cretaceous) – Northern Yellowstone area – Yellow-gray to medium-gray sandstone; tuffaceous and carbonaceous in lower portion (Love and Christiansen, 1985). [Exposed in the northern Yellowstone area of Wyoming.]
Frontier Formation (Kf) (Upper Cretaceous) – Northern Wyoming – Interbedded gray sandstone and sandy shale (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Lower Cretaceous geologic units - Wyoming

Kft *Upper and Lower Cretaceous: sandstone and shale.*
Frontier Formation, Mowry Shale, and Thermopolis Shale (Kft) (Lower to Upper Cretaceous) [Exposed in northern Wyoming and the northern Yellowstone area of Wyoming.]
Frontier Formation (Kft) (Upper Cretaceous) – Northern Yellowstone area – Yellow-gray to medium-gray sandstone; tuffaceous and carbonaceous in lower portion (Love and Christiansen, 1985).
Frontier Formation (Kft) (Upper Cretaceous) – Northern Wyoming – Gray sandstone and sandy shale (Love and Christiansen, 1985).
Mowry Shale (Kft) (Upper Cretaceous) – Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds (Love and Christiansen, 1985).
Thermopolis Shale (Kft) (Lower Cretaceous) – Black soft fissile shale; **Muddy Sandstone** at top" (Love and

Christiansen, 1985).

Kmt *Lower Cretaceous: shale and sandstone.**

Mowry and Thermopolis Shales (Kmt) (Lower to Upper Cretaceous) [Exposed in northern Wyoming.]

Mowry Shale (Kmt) (Upper Cretaceous) – Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds (Love and Christiansen, 1985).

Thermopolis Shale (Kmt) (Lower Cretaceous) – Black soft fissile shale; **Muddy Sandstone** at top of unit (Love and Christiansen, 1985).

Jurassic geologic units - Wyoming

KJ *Upper Jurassic-Lower Cretaceous: sandstone and claystone.**

Cloverly and Morrison Formations (KJ) (Jurassic to Lower Cretaceous) [Exposed in northern Wyoming.]

Cloverly Formation (KJ) – Rust-color sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base (Love and Christiansen, 1985).

Morrison Formation (KJ) – Dull, variegated siliceous claystone, nodular white limestone, and gray silty sandstone (Love and Christiansen, 1985).

KJs *Middle Jurassic-Lower Cretaceous: fine-grained mixed clastic and medium-grained mixed clastic rocks.*

Cloverly, Morrison, and Sundance Formations (KJs) (Jurassic to Lower Cretaceous) [Exposed in northern Wyoming.]

Cloverly Formation (KJs) – Rust-color sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base (Love and Christiansen, 1985).

Morrison Formation (KJs) – Dull, variegated siliceous claystone; nodular white limestone; and gray silty sandstone (Love and Christiansen, 1985).

Sundance Formation (KJs) – Green-gray glauconitic sandstone and shale, underlain by red and gray, non-glauconitic sandstone and shale (Love and Christiansen, 1985).

KJg *Middle Jurassic-Lower Cretaceous: fine-grained mixed clastic and medium-grained mixed clastic rocks.**

Cloverly, Morrison, Sundance, and Gypsum Spring Formations (KJg) (Jurassic to Lower Cretaceous) [Exposed in northern Wyoming.]

Cloverly Formation (KJg) – Rust-color sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base (Love and Christiansen, 1985).

Morrison Formation (KJg) – Dull, variegated siliceous claystone; nodular white limestone; and gray silty sandstone (Love and Christiansen, 1985).

Sundance Formation (KJg) – Green-gray glauconitic sandstone and shale, underlain by red and gray, non-glauconitic sandstone and shale (Love and Christiansen, 1985).

Gypsum Spring Formation (KJg) – Interbedded red shale, dolomite, and gypsum; wedges out southward in T39N in northern Wyoming (Love and Christiansen, 1985).

KJk *Middle Jurassic-Lower Cretaceous: fine-grained mixed clastic and medium-grained mixed clastic rocks.*

Ellis Group; also Kootenai Formation, and **Morrison Formation** (KJk) (Jurassic to Lower Cretaceous) [Exposed in northern Yellowstone area of Wyoming.]

Kootenai Formation (KJk) – Rust-color thin-bedded sandstone, gray-red soft claystone, white limestone, and chert-pebble conglomerate (Love and Christiansen, 1985).

Morrison Formation (Jurassic) – Variegated silty claystone and fine-grained sandstone (Love and Christiansen, 1985).

Ellis Group (KJk) – *Swift Formation (KJk)* – Calcareous glauconitic sandstone and sandy limestone (upper unit of Ellis Group); *Rierdon Formation (KJk)* – Mudstone, siltstone, shale, and basal limestone (middle unit of Ellis Group); and *Sawtooth Formation (KJk)* – Red beds and limestone (lower unit of Ellis Group) (Love and Christiansen, 1985).

KT̄R *Middle Jurassic-Upper Jurassic: sandstone and shale.*

Cloverly, Morrison, Sundance and Gypsum Spring Formations, and Nugget Sandstone (KT̄R) (Triassic(?) to Jurassic to Lower Cretaceous) [Exposed in northern Wyoming.]

Cloverly Formation (KT̄R) (Lower Cretaceous) – Rust-color sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base (Love and Christiansen, 1985).

Morrison Formation (KT̄R) (Jurassic) – Dull, variegated siliceous claystone; nodular white limestone; and gray silty sandstone (Love and Christiansen, 1985).

Sundance Formation (KT̄R) (Jurassic) – Green-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale (Love and Christiansen, 1985).

Gypsum Spring Formation (KŦ) (Jurassic) – Interbedded red shale, dolomite, and gypsum; wedges out southward in T39N (Love and Christiansen, 1985).

Nugget Sandstone (KŦ) (Triassic (?) to Jurassic (?)) – Gray to dull-red crossbedded quartz sandstone (Love and Christiansen, 1985). The KŦ unit includes a wedge edge of Nugget Sandstone in T.34N., R.88W. and T.32N., R.91W. (Love and Christiansen, 1985).

Js *Middle Jurassic-Upper Jurassic: sandstone and shale.*

Sundance Formation (Js) (Middle Jurassic to Upper Jurassic) – Green-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Jsg *Upper Triassic-Middle Jurassic: sandstone and shale.**

Sundance Formation and Gypsum Spring Formation (Jsg) (Upper Triassic to Middle Jurassic) [Exposed in northern Wyoming.]

Sundance Formation (Jsg) (Jurassic) – Green-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale (Love and Christiansen, 1985).

Gypsum Spring Formation (Jsg) (Jurassic) – Interbedded red shale, dolomite, and gypsum (Love and Christiansen, 1985). In northern Wyoming, the Gypsum Spring Formation wedges out southward in T.39N. (Love and Christiansen, 1985).

JŦ *Triassic(?)-Jurassic(?): sandstone and shale.*

Sundance Formation, Gypsum Spring Formation, and Nugget Sandstone (JŦ) (Triassic (?) to Upper Jurassic) – [Exposed in the northern Wyoming.]

Sundance Formation (JŦ) (Jurassic) – Green-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale (Love and Christiansen, 1985).

Gypsum Spring Formation (JŦ) (Jurassic) – Interbedded red shale, dolomite, and gypsum (Love and Christiansen, 1985).

Nugget Sandstone (JŦ) (Triassic(?) to Jurassic) – Northern Wyoming – Gray to dull-red crossbedded, quartz-rich sandstone (Love and Christiansen, 1985).

JŦgn *Triassic(?)-Upper Jurassic: sandstone and fine-grained mixed clastic rocks.*

Gypsum Spring Formation and Nugget Sandstone (JŦgn) (Triassic(?) to Jurassic) [Exposed in northern Wyoming.]

Gypsum Spring Formation (JŦgn) (Jurassic) – Interbedded red shale, dolomite, and gypsum (Love and Christiansen, 1985).

Nugget Sandstone (JŦgn) (Triassic (?) to Jurassic) – Northern Wyoming – Gray to dull-red crossbedded, quartz-rich sandstone (Love and Christiansen, 1985).

JŦn *Triassic(?)-Jurassic: sandstone.*

Nugget Sandstone (JŦn) (Triassic(?) to Jurassic) – Northern Wyoming – Gray to dull-red crossbedded quartz-rich sandstone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

JŦgc *Lower Triassic-Upper Jurassic: fine-grained mixed clastic and carbonate rocks.*

Gypsum Spring Formation, Nugget Sandstone, and Chugwater Formation (JŦgc) (Triassic to Jurassic) [Exposed in northern Wyoming.]

Gypsum Spring Formation (JŦgc) (Jurassic) – Interbedded red shale, dolomite, and gypsum (Love and Christiansen, 1985).

Nugget Sandstone – (JŦgc) (Triassic (?) to Jurassic) – North Wyoming – Gray to dull-red crossbedded, quartz-rich sandstone (Love and Christiansen, 1985).

Chugwater Formation – (JŦgc) (Triassic) – Red siltstone and shale; **Alcova Limestone Member** in upper middle part of formation in northern Wyoming; thin gypsum partings near base in northern Wyoming (Love and Christiansen, 1985).

Triassic geologic units - Wyoming

Ŧc *Lower Triassic-Upper Triassic: siltstone and shale.**

Chugwater Formation (Ŧc) (Lower Triassic to Upper Triassic) – Red siltstone and shale; **Alcova Limestone Member** in the upper middle part of the formation; thin gypsum partings near base in northern Wyoming (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

Ŧcd *Lower Triassic-Upper Triassic: mudstone and limestone.*

Chugwater Formation and Dinwoody Formation (ŦRcd) (Lower Triassic to Upper Triassic) [Exposed in northern Wyoming and the northern Yellowstone area of Wyoming.]

Chugwater Formation (ŦRcd) – Red siltstone and shale; **Alcova Limestone Member** in the upper middle part of the formation; thin gypsum partings near base in northern Wyoming (Love and Christiansen, 1985).

Dinwoody Formation (ŦRcd) – Olive-drab, hard, dolomitic, thin-bedded siltstone and green shale (Love and Christiansen, 1985).

ŦRPcg *Permian-Lower Triassic: siltstone and sandstone.*

Chugwater Formation and Goose Egg Formation (ŦRPcg) (Permian to Lower Triassic) [Exposed in northern Wyoming.]

Chugwater Formation (ŦRPcg) – Red shale and siltstone with thin gypsum partings near base (Love and Christiansen, 1985).

Goose Egg Formation (ŦRPcg) – Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone (Love and Christiansen, 1985).

ŦRPg *Permian-Lower Triassic: mudstone and carbonate rock.**

Goose Egg Formation (ŦRPg) (Permian to Lower Triassic) – Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

PALEOZOIC GEOLOGIC UNITS - Wyoming

MzPz *Upper Mississippian-Lower Cretaceous: sedimentary rock units and clastic rocks.**

Mesozoic and Paleozoic rocks (northern Wyoming) (Paleozoic to Mesozoic) [Exposed in northern Wyoming.] – Mapped in small local areas of complex structure.

Mesozoic and Paleozoic rocks (MzPz) – East flank of Absaroka Range – **Dinwoody Formation**, **Phosphoria Formation** and related rocks, **Tensleep Sandstone**, and **Amsden Formation** (Lower Triassic through Upper Mississippian) (Love and Christiansen, 1985).

Pp *Permian: shale and phosphorite rocks.**

Phosphoria Formation and related rocks (Pp) (Permian) – Brown sandstone, brown dolomite, cherty phosphatic and glauconitic dolomite, phosphatic sandstone and dolomite, and green-gray to black shale; intertonguing equivalents of parts of Phosphoria are **Park City Formation** (cherty dolomite, limestone, and phosphatic gray shale) and Shedhorn Sandstone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

PIPM *Upper Mississippian-Permian: limestone and sandstone.*

Phosphoria, Wells, **and Amsden Formations** (PIPM) (Upper Mississippian to Pennsylvanian to Permian) – Upper part composed of dark- to light-gray chert and shale with black shale and phosphorite at top; lower part consists of black shale, phosphorite, and cherty dolomite (Love and Christiansen, 1985). [Exposed in the Overthrust Belt of western Wyoming.]

PIPMa *Upper Mississippian-Permian: limestone and sandstone.*

Phosphoria Formation and related rocks; Quadrant Sandstone, and **Amsden Formation** (PIPMa) (Upper Mississippian to Pennsylvanian to Permian) [Exposed in the northern Yellowstone area of Wyoming.]

Phosphoria Formation and related rocks (PIPMa) (Permian) – Brown sandstone, brown dolomite, cherty phosphatic and glauconitic dolomite, phosphatic sandstone and dolomite, and green-gray to black shale; intertonguing equivalent is Shedhorn Sandstone (Love and Christiansen, 1985).

Quadrant Sandstone (PIPMa) – Light-gray sandstone (Love and Christiansen, 1985).

Amsden Formation (PIPMa) – Red and green shale and dolomitic shale, siltstone, and sandstone (Love and Christiansen, 1985).

PM *Upper Mississippian-Permian: sandstone and carbonate rocks.**

Tensleep Sandstone and Amsden Formation (PM) (Upper Mississippian to Lower Permian) [Exposed in northern Wyoming.]

Tensleep Sandstone (PM) (Upper Mississippian to Lower Permian) – Northern Wyoming – White to gray sandstone interbedded with thin limestone and dolomite beds (Love and Christiansen, 1985).

Amsden Formation (PM) (Upper Mississippian to Middle Pennsylvanian) – Northern Wyoming – Red and green shale and dolomite with persistent red to brown sandstone at base (Love and Christiansen, 1985).

Mm *Lower Mississippian-Upper Mississippian: limestone and dolostone (dolomite).**

Madison Limestone or Group (Mm) (Lower to Upper Mississippian) – The **Madison Limestone** includes and upper

member composed of blue-gray, massive limestone and a lower member of gray, cherty limestone and dolomite; includes a wedge edge of **Bighorn Dolomite** in Tps. 43 and 44 N., Rs. 85 and 86 W. (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

MD *Upper Devonian-Upper Mississippian: limestone and dolostone (dolomite).**

Madison Group, **Three Forks Formation, and Jefferson Formation** (MD) (Upper Devonian to Upper Mississippian) [Exposed the northern Yellowstone area of Wyoming.]

Madison Group (MD) (Lower to Upper Mississippian) – Composed of an upper member of blue-gray massive limestone and dolomite, and a lower member of gray cherty limestone and dolomite (Love and Christiansen, 1985).

Three Forks Formation (MD) (Devonian) – Pink, yellow, and green dolomitic siltstone and shale (Love and Christiansen, 1985).

Jefferson Formation (MD) (Devonian) – Siliceous, massive dolomite (Love and Christiansen, 1985).

MO *Middle Ordovician-Upper Mississippian: limestone and dolostone (dolomite).*

Madison Limestone and Bighorn Dolomite (MO) (Ordovician to Upper Mississippian) [Exposed in northern Wyoming.]

Madison Limestone (MO) (Lower to Upper Mississippian) – Composed of an upper member of blue-gray massive limestone and dolomite, and a lower member of gray cherty limestone and dolomite (Love and Christiansen, 1985).

Bighorn Dolomite (MO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985).

MDO *Middle Ordovician-Upper Mississippian: carbonate rock and mudstone.*

Madison Limestone, Darby or Three Forks, Jefferson, and Beartooth Butte Formations, and Bighorn Dolomite (MDO) (Ordovician to Upper Mississippian) [Exposed in northern Wyoming.] East of the Wind River Canyon, the unit consists of Madison, Bighorn, and Cambrian rocks; in the Rattlesnake Hills and the east end of the Granite Mountains, the MDO unit is composed of Madison Limestone and Cambrian rocks (Love and Christiansen, 1985).

Madison Limestone (MDO) (Lower to Upper Mississippian) – Composed of an upper member of blue-gray massive limestone and dolomite and a lower member of gray cherty limestone and dolomite (Love and Christiansen, 1985).

Darby Formation (MDO) (Upper Devonian to Lower Mississippian) – Yellow and green-gray shale and dolomitic siltstone underlain by fetid brown dolomite and limestone (Love and Christiansen, 1985). [Exposed on the west flank of the Washakie Range of northwestern Wyoming.]

Three Forks Formation (MDO) (Devonian) – Pink, yellow, and green dolomitic siltstone and shale (Love and Christiansen, 1985).

Jefferson Formation (MDO) (Devonian) – Massive siliceous dolomite (Love and Christiansen, 1985).

Beartooth Butte Formation (MDO) (Lower Devonian) – Red sandstone, limy siltstone, and limestone (Love and Christiansen, 1985). [Exposed only in the Beartooth Mountains of northwestern Wyoming.]

Bighorn Dolomite (MDO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985).

DO *Middle Ordovician-Upper Devonian: carbonate rock and mudstone.**

Three Forks and Jefferson Formations and Bighorn Dolomite (DO) (Ordovician to Devonian) [Exposed in the northern Yellowstone area of Wyoming.]

Three Forks Formation (DO) (Devonian) – Pink, yellow, and green dolomitic siltstone and shale (Love and Christiansen, 1985).

Jefferson Formation (DO) (Devonian) – Massive siliceous dolomite (Love and Christiansen, 1985).

Bighorn Dolomite (DO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985).

Three Forks, Jefferson, and **Beartooth Butte Formations, and Bighorn Dolomite** (DO) (Ordovician to Devonian) [Exposed in northern Wyoming.]

Three Forks Formation (DO) (Devonian) – Pink, yellow, and green dolomitic siltstone and shale (Love and Christiansen, 1985).

Jefferson Formation (DO) (Devonian) – Massive siliceous dolomite (Love and Christiansen, 1985).

Beartooth Butte Formation (DO) (Lower Devonian) – Red sandstone, limy siltstone, and limestone (Love and Christiansen, 1985). [Exposed only in Beartooth Mountains of northwestern Wyoming.]

Bighorn Dolomite (DO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985).

Ob *Middle Ordovician-Upper Ordovician: dolostone (dolomite).**

Bighorn Dolomite (Ob) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985). [Exposed in northern Wyoming.]

O€ *Middle Cambrian-Upper Ordovician: limestone and dolostone (dolomite).**

Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone (O€) (Middle Cambrian to Upper Ordovician) [Exposed in northern Wyoming.]

Bighorn Dolomite (DO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and local dolomitic limestone (Love and Christiansen, 1985).

Gallatin Limestone (O€) (Upper Cambrian) – Gray and tan limestone (Love and Christiansen, 1985).

Gros Ventre Formation (O€) (Middle to Upper Cambrian) – Soft, green, micaceous shale (Upper and Middle Cambrian Park Shale Member), underlain by blue-gray and yellow, mottled hard dense limestone (Middle Cambrian Death Canyon Limestone Member), and soft, green micaceous shale (Middle Cambrian Wolsey Shale Member) (Love and Christiansen, 1985).

Flathead Sandstone (O€) (Middle Cambrian) – Dull-red, quartz-rich sandstone (Love and Christiansen, 1985).

Bighorn Dolomite, **Snowy Range Formation, Pilgrim Limestone**, Park Shale, Meagher Limestone, Wolsey Shale, **and Flathead Sandstone** (O€) (Middle Cambrian to Upper Ordovician) [Exposed in the northern Yellowstone area of Wyoming.]

Bighorn Dolomite (DO) (Middle to Upper Ordovician) – Gray, cliff-forming, siliceous, massive dolomite and locally dolomitic limestone (Love and Christiansen, 1985).

Snowy Range Formation (O€) (Upper Cambrian) – Medium-gray limestone underlain by green-gray shale (Love and Christiansen, 1985).

Pilgrim Limestone (O€) (Upper Cambrian) – Hard, blue-gray and yellow mottled limestone (Love and Christiansen, 1985).

Park Shale (O€) (Middle to Upper Cambrian) – Soft, green micaceous shale; upper part may be Upper Cambrian (Love and Christiansen, 1985).

Meagher Limestone (O€) (Middle Cambrian) – Hard, blue-gray and yellow mottled limestone (Love and Christiansen, 1985).

Wolsey Shale (O€) (Middle Cambrian) – Composed of soft, green micaceous shale (Love and Christiansen, 1985).

Flathead Sandstone (O€) (Middle Cambrian) – Dull-red quartz-rich sandstone (Love and Christiansen, 1985).

€r *Middle Cambrian-Upper Cambrian: limestone and sandstone.**

Cambrian rocks (€r) (Middle to Upper Cambrian) – Composed of hard, blue-gray and yellow mottled, dense limestone interbedded with soft, green micaceous shale; dull-red quartz-rich sandstone at base (Love and Christiansen, 1985).

PRECAMBRIAN GEOLOGIC UNITS - Wyoming

[p€r] [***Precambrian rocks*** *– combines the geologic units below on Plate I*]*

shear [~] *Precambrian: Archean: tectonite in a shear zone.*

[Shown with a wavy pattern ~ on the state map (Love and Christiansen, 1985). Exposed only in the northern Wind River Range.]

Wgn *Precambrian: Late Archean: granitic gneiss.*

Granite gneiss (Wgn) (Precambrian – Late Archean, 2,600-3,100+ Ma) – Layered to massive, locally migmatitic gneiss; metasedimentary and metavolcanic rocks locally common (Love and Christiansen, 1985). [Exposed in the Wind River Range.]

WVsv *Precambrian: Middle Archean-Late Archean: metasedimentary rocks and metavolcanic rocks.*

Metasedimentary and metavolcanic rocks (WVsv) (Precambrian – Middle Archean to Late Archean, 2,600-3,200+ Ma) – 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 (Love and Christiansen, 1985). [Exposed in the Wind River Range.]

Ws *Precambrian: Late Archean: metasedimentary rocks.*

Metasedimentary rocks (Ws) (Precambrian – Late Archean, 2,800+ Ma) – Metagraywacke, pelitic schist, metaconglomerate, graphitic schist, and iron-formation; local meta-andesite (Love and Christiansen, 1985). [Exposed in the southern Wind River Range.]

Wmu *Precambrian: Late Archean: metamorphosed mafic and ultramafic rocks.* (Love and Christiansen, 1985)

Wg *Precambrian: Late Archean: granitoid rocks.*
Granitic rocks of 2,600-Ma Age Group (Wg) (Precambrian – Late Archean, 2,600 Ma)
Granitic rocks (Wg) (Precambrian – Late Archean) – Granodiorite to porphyritic and equigranular granite (Love and Christiansen, 1985). [Exposed in the Wind River Range.]

Wgd *Precambrian: Late Archean: granodiorite rocks.*
Granodiorite of the Louis Lake Pluton (Wgd) (Precambrian – Late Archean, 2,640 Ma) – Equigranular; locally gneissic (Love and Christiansen, 1985). [Exposed only in the southern Wind River Range.]

WVg *Precambrian: Middle Archean-Late Archean: granitoid rocks.*
Plutonic rocks (WVg) (Precambrian – Middle Archean to Late Archean) – Wind River Range – Largely granite gneiss; contains diorite and quartz diorite facies (Love and Christiansen, 1985). [Exposed only in the northern Wind River Range.]

Ugn *Precambrian: Early Archean: granite gneiss and migmatite rocks.*
Oldest gneiss complex (Ugn) (Precambrian – Early Archean) – Layered granitic gneiss, locally migmatitic. Local masses of quartzite, metagraywacke, iron-formation, and other metasedimentary rocks and amphibolite and felsic gneiss thought to be volcanic. Includes large bodies of metagabbro. Inclusions show evidence of granulite-facies metamorphism prior to 2,800 Ma (Love and Christiansen, 1985). [Located in the northern Wind River Range.] The Early Archean gneiss complex contains the oldest rocks in Wyoming.

Ugn + *Precambrian: Early Archean: granite gneiss and migmatite rocks*.
Oldest gneiss complex (Precambrian – Early Archean) – Area of migmatite related to emplacement of 2,600-Ma granite (Love and Christiansen, 1985). These are the oldest rocks in Wyoming. [Located in the northern Wind River Range.] Shown with an overprint pattern (+) in the Ugn unit on the state map (Love and Christiansen, 1985).

Appendix B

Wyoming Water Development Commission studies

Wyoming Water Development Commission studies

Study*	Location	Aquifer(s)†	Project description	Results/recommendations	Notes/subsequent action
Anderson and Kelly Inc., 1982	**Thermopolis**, Hot Springs Co.	Park City Tensleep Madison	Determine geothermal resource possibilities, estimate quantity and temperature of resources, and estimate costs of development.	Water is under artesian pressure in Paleozoic aquifers and decreases in temperature from Rose Dome (160°F) to Thermopolis Anticline (100°F). Development could reduce flow to Hot Springs State Park.	Review and proceed with recommendations in the report.
Buell Winter Mousel and Associates, 1982; 1983	**Manderson**, Big Horn Co.	Mesaverde	Explore alternate/additional water supply for increased reliability.	Abandon idea of Mesaverde formation for water supply; consider Lance formation.	Site Selection for exploratory drilling into formations fitting requirements
John W. Donnell and Associates, 1982	**Greybull**, Big Horn Co.	Tensleep Madison- Bighorn Flathead	Evaluate capability of a water system to meet present and potential water demands.	A test well should be drilled and properly cemented and cased to provide adequate flow.	Source of future water will be discussed by the town officials.
Western Water Consultants, 1982a; 1983a	**Byron**, Big Horn Co.	All aquifers	Assess all ground water resources inclusive of the Cambrian through Quaternary sediments.	Best potential for water is in alluvium and the Madison Formation.	Proceed with drilling of sites to test quality checking and flow potential.
Western Water Consultants, 1982b; 1983b	**Cowley**, Big Horn Co.	All aquifers	Assess all ground water resources inclusive of the Cambrian through Quaternary sediments.	Best potential for flow and water quality water is in alluvium or Madison aquifer.	Proceed with drilling of sites to test quality checking and flow potential.
Big Horn Engineering, 1983	**Greybull**, Big Horn Co.	Tensleep Madison- Big Horn Flathead	Investigate feasibility of supplementary ground water supply for the town of Greybull	Potential sources of water are Shell Creek, the Big Horn River, and groundwater from listed aquifers. Recommendations for development, if necessary, of the Madison aquifer.	Review and proceed with recommendations in the report.
Western Water Consultants, 1983c; 1984	**Manderson**, Big Horn Co.	Tensleep Madison- Bighorn Flathead	Evaluate ground-water development potential for saturated and permeable rock units in the vicinity of Manderson.	Aquifers tested provide adequate supply and water quality.	Continue with cost evaluation and well location.
Morrison-Mairle, Inc, 1985	**Hudson**, Fremont Co.	Wind River Fort Union Lance	Evaluate water use, population trends, and future water demands.	Water levels will drop below the level of the wells if they are run at maximum capacity longer than seven days without recharge. Reduction of pumping rate advised.	Reduction of pumping rates to provide water during peak use times.

Continued.

Wyoming Water Development Commission studies

Study*	Location	Aquifer(s)†	Project description	Results/recommendations	Notes/subsequent action
Western Water Consultants, 1985, 1986	**Frannie**, **Deaver**, Park Co.	Tensleep Madison-Bighorn Flathead	Determine best location and aquifer for increased water supply wells.	Adequate supply and water quality found in the Madison aquifer.	The new well will remove Frannie from its current problems with Radium-226.
Morrison-Mairle, Inc, 1986	**Shell Valley**, Washakie Co.	Madison-Bighorn	Determine feasibility of developing groundwater sources for agricultural supply.	Test well flow and water quality sufficient for agricultural use.	Evaluate alternatives and proceed.
Nelson Engineering, 1992	**Dubois**, Fremont Co.	Alluvial	Preliminary investigation of potential aquifers and drilling and testing of wells.	Two locations chosen for ease of drilling and location.	Test well one drilled, plugged, and abandoned due to lack of water.
Jorgenson Engineering, 1993a,b; 1995	**Upper Little Warm Springs**, Fremont Co.	Tensleep	Potential water supply for the Upper Little Warm Springs subdivision.	Water quality and temperature not within drinking water standards. Deeper drilling could only result in decreased water quality.	No further progress made on this issue.
Graham, Dietz & Associates, 1994a,b,c	**Manderson**, Big Horn Co.	Madison-Bighorn	Feasibility study for possible water supply sources for the town of Manderson.	Well completed in Big Horn aquifer, quality meets EPA water quality standards, can produce 270 gpm with continuous use over 40 years.	Project feasible due to high public support, increased quality of living, and low cost to individuals.
BRS Inc., 1995a,b	**Thermopolis**, Hot Springs Co.	Alluvial Chugwater	Evaluate water supply alternatives and costs for Black Willow Water District.	Deep ground water use limited due to geothermal activity.	Review and proceed with recommendations in the report.
Engineering Associates, 1995a,b	Rural **Washakie County**	Madison	Investigate feasibility of providing rural water services to areas surrounding Worland.	Drilling new wells would not be practical, incremental increase in current water production would not have a significant impact on the aquifer.	Review and proceed with recommendations in the report.
Nelson Engineering, 1995a,b; 1997a,b	**Greybull**, Big Horn Co.	Tensleep Madison	Determine most cost effective way to provide potable water to consumers.	Current production sufficient for current and projected use.	Continue with recommendations
Nelson Engineering, 1998a,b; 1999a,b	**Lander**, Fremont Co.	Alluvial and glacial terrace deposits	Further investigate potential for groundwater development.	Test well site could potentially supply significant amounts of high quality water not under direct influence from the surface.	Refine current water sources based on the findings of the study.

Continued.

Wyoming Water Development Commission studies

Study*	Location	Aquifer(s)†	Project description	Results/recommendations	Notes/subsequent action
JFC Engineers /Surveyors, 1996a,b	**Lander**, Fremont Co.	Tensleep	Create a base knowledge for creation of a master plan after evaluating existing infrastructure.	Development of groundwater could supply water to areas outside the hydraulic limits of the distribution system.	No project features being considered for construction at this time.
BRS Inc., 1998a,b	**McNutt**, Washakie Co.	Fort Union (Willwood Member) Madison-Bighorn	Determine feasibility of establishing public water supply system within the McNutt District.	Development cost and low potential for successful completion prohibit deep groundwater use.	Review and proceed with recommendations in the report.
BRS Inc., 1998c,d	Rural **Washakie County**	Madison-Bighorn	Level II feasibility study of preferred options for water supply.	Current peak demand of city of Worland accounts for 15% of max production of groundwater under current artesian flow potential.	Recommendation that the Washakie Rural project be advanced to Level III
Engineering Associates, 1998a,b	**Greybull**, Big Horn Co.	N/A	Examine feasibility of providing water service to rural areas.	Recommendations for increased use of existing wells and storage of overproduction in off-peak usage times.	Review and proceed with recommendations in the report.
James Gores and Associates, P.C., 1998a,b	**Riverton**, Fremont Co.	N/A	Quantify water needs for Riverton Region, and create a plan for meeting them.	Wells completed in the "middle zone" (4,001-4,400 ft) provided the best high-quality drinking water.	Supply source decision pending evaluation of cost to water recipients.
James Gores and Associates, P.C., 1999a,b	**Dubois**, Fremont Co.	Alluvial	Locate potential sources for future development.	Best location for new wells is near current wells in the producing field.	Current demand does not warrant any further development at this time.
Engineering Associates, 2000a,b	**Powell**, Park Co.	N/A	Determine if Powell's Municipal Airport has ground water opportunities for expansion.	A well drilled to ~300ft would yield sufficient, but not potable, water.	Estimation of costs to accurately predict the financial impacts.
BRS & Lidstone and Anderson Inc., 2002 [component of Forsgren Associates, 2004]	Rural **Worland**, Washakie Co.	Madison	Expansion of northern regional system. Development of a well field in the Big Trails vicinity.	Expansion of existing source not recommended due to reliance on a single well field. Close proximity to recharge and flows make the Big Trails option preferred.	Level III cost estimate completed.
Lidstone and Associates, Inc., 2002b	**Ten Sleep**, Washakie Co.	Amsden Madison	Determine current water needs and possible sources if expansion is necessary.	Improve infrastructure, increase monitoring of existing wells, and increase water rights.	Improve water supply, storage, and distribution according to the report.

Continued.

Wyoming Water Development Commission studies

Study*	Location	Aquifer(s)†	Project description	Results/recommendations	Notes/subsequent action
Lidstone and Associates, Inc., 2002a	**Hyattville**, Washakie Co.	Madison	Evaluate current water supply system to identify causes of failure in quantity of distribution.	Lack of sufficient production from current well system the result of a leak in the well.	Lack of adequate supply during peak demand was identified to be the problem.
Weston Engineering Inc., 2002a, 2004a, 2007a,	**Lander**, Fremont Co.	Nugget Tensleep Madison	Investigate possible sources to relieve municipal use of surface water for the town of Lander.	Recommendation for well completion in the Madison aquifer.	Obtain permission for well location and drilling. Monitor well production and shut-in pressure.
BRS Inc., 2003a,b,c,d,e	**Wind/Bighorn River Basin**	Wind River Madison	13 aquifers identified as important groundwater sources, the Madison and Wind River being the most utilized. Groundwater is primary source for many uses.	Declining water level and wellhead pressure reported near Hyatteville and Riverton.	GIS and electronic components are intended to allow for growth with new information.
Engineering Associates, 2003a,b,c	**Greybull**, Big Horn Co.	Alluvial	Evaluate available raw water supply sources.	Alluvial groundwater would be the most viable source of supply.	Recommendations included utilization of water from Lower Shell Creek.
Forsgren Associates, 2004a,b	Rural **Hot Springs County**; rural **Worland** [*pipeline*]	Madison	Investigate possible expansion/ improvements to existing groundwater supply.	Utilize Buffalo Creek well #2 and possibly other groundwater sources to increase water supply.	Determine costs and funding sources for completion and distribution of wells and water.
Lidstone and Associates, Inc., 2004a,b	**Ten Sleep**, Washakie Co.	Madison	Test and determine sustainable yield of current Ten Sleep wells.	Both wells capable of yielding large artesian flow.	Modification and repair of existing infrastructure for Tensleep wells #1 and #2.
Nelson Engineering, 2004a,b	**Owl Creek**, Hot Springs Co.	Tensleep Madison	Evaluate potential for providing additional water supply.	Recommend a deep aquifer test well.	Deep aquifer test well should be located in lower Mud Creek.
Stetson Engineering, Inc, 2004	**Dubois**, Fremont Co.	Alluvial	Identify candidate sites for test wells.	Producible and sustainable water located to meet needs of increased demand.	Recommendations for completing the wells and producing at designated rates.
Falcon Consulting Services L.L.C., 2005	**Frannie**, Park Co.	Madison	Determine feasibility of rehabilitating existing well to productive status.	Options: continue capture from existing well, rehabilitate well, plug and abandon well.	Determine costs and funding sources for options provided.

Continued.

Wyoming Water Development Commission studies

Study*	Location	Aquifer(s)†	Project description	Results/recommendations	Notes/subsequent action
Engineering Associates, 2006a,b; 2007a,b	**Thermopolis**, **South Thermopolis**, Hot Springs Co.	Madison	Evaluate possible improvements to water system serving South Thermopolis Water and Sewer District.	Groundwater sources insufficient in volume produced, quality, and well location.	Current demand for water in the district does not require addition sources.
Wester Wetstein and Associates, 2006a,b	**Hyattville**, Washakie Co.	Madison Bighorn	Determine alternative groundwater supply sources.	Test wells showed adequate flow and quality.	Recommendation for construction of second storage tank to increase peak demand supply.
Engineering Associates, 2007a,b	**Owl Creek** rural water supply	Madison	Determine feasibility of providing water to rural locations west of Thermopolis.	Use Madison aquifer water, Alternative V, following increased use of various other current sources.	Recommendation for connection with Thermopolis municipal water supply.
TST, Inc., 2007a,b	**Burlington**, Big Horn Co.	Alluvial	Investigate expansion of the rural water system.	Wells capable of meeting future demand for the next 30 years.	Alter distribution and control of current water supply.
Aqua Engineering, 2008	**Frannie**, Park Co.	Not Specified	Investigate and describe raw water supply sources. Identify service area and demand projections.	Sources providing 80.5 acre-feet/year: Kirk Well #1, Shoshone Municipal Pipeline System, Sage Creek, Shoshone Project. Deep well sources do not meet water-quality standards.	Phase II work was not continued except as was requested by the WWDC
Keller Associates, 2008a,b	**Mountain View Acres**, **Riverton** Fremont Co.	Wind River	Determine feasibility of combining the City of Riverton and Mountain View Acres water supplies.	Well #17 in Wind River Aquifer has water quality and volumes that would allow for adequate expansion.	The project outlined would fit all future water demand.
Lidstone and Associates, Inc., 2008a,b	**Shoshone**, Fremont Co.	Tensleep Madison	Complete a high capacity municipal supply well to provide supplemental ground water supply.	Full source redundancy is expected with two additional Tensleep aquifer wells.	Obtain the necessary land and permits to construct the wells that are needed to create the redundant system.
Stetson Engineering, Inc, 2006a,b, 2008a,b	**Lysite**, Fremont Co.	Alluvial Wind River	Determine sources of supply for Lysite Water and Sewer District.	Alluvial sources were shown to be more cost effective and suitable for needs of district.	Move forward with recommendations.
James Gores and Associates, P.C., 2009a,b	**Hudson**, Fremont Co.	Wind River Fort Union Madison	Analyze water supply options available to the Town of Hudson.	Water produced from these wells would meet current EPA drinking water standards.	Existing supply would be sufficient provided a treatment plant can be constructed.

*See References for complete entries.

†Aquifers are identified as formations in many reports.

Appendix C

GIS Data and Sources

Dataset	Presented in	Source
Basin boundaries and hydrologic divide	Plates I, IV, VII, VIII, X, Figs. 1-1, 3-1 to 3-3, 4-1, 5-1 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	Modified from U.S. Department of Agriculture, 2002
GEOLOGY		
Montana geology	Plate I	Modified from Vuke, Porter, et al., 2007
Precambrian basement structure contour	Plate I	Modified from Blackstone, 1993
Structural divide between the Wind River and Bighorn Basins	Figs. 3-1 and 3-2	Interpreted from Stoeser, Green, et al., 2005
WBRB cross-section lines	Plate I	Digitized from Finn et al., 2010; Keefer, 1970; Libra, Doremus, and Goodwin, 1981; Lowry, Lowham, and Lines, 1976; Nuccio and Finn, 1998; Richter, 1981; Stone, 2004; and Sundell, 1993
WBRB Lineaments	Plates IV, X	Digitized from Cooley, 1986b
Wyoming and Montana faults	Plates I, IV	Modified from Stoeser, Green, et al., 2005
Wyoming and Montana hydrogeology (includes aquifer outcrop areas)	Plates IV, VII, VIII, X, Fig 4-1, 5-3 to 5-9, 6-2 to 6-6, 7-1, 8-1 to 8-10	Modified from Stoeser, Green, et al., 2005, and Plates II and III of this report
Wyoming geology	Plate I	Modified from Stoeser, Green, et al., 2005
GROUNDWATER		
Anomalous geothermal gradients	Fig. 4-1	Digitized from Heasler and Hinckley, 1985, and Hinckley and Heasler, 1987
Aquifer recharge as a percent of precipitation	Fig. 6-1	Modified from Hamerlinck and Arneson, 1998, and Daly and Taylor, 1998
Aquifer sensitivity	Fig. 5-2	Hamerlinck and Arneson, 1998
Average annual precipitation, 1961-1990	Fig. 3-3	Daly and Taylor, 1998
Environmental water sample locations	Fig. 7-1	USGS, Environmental water sample locations GIS dataset of 2010
Estimated net annual aquifer recharge	Figs. 5-1, 6-2 to 6-6	Hamerlinck and Arneson, 1998
Montana groundwater wells	Plates IV, X, Figs. 8-2, 8-7, 8-9, 8-10	Montana Bureau of Mines and Geology, Montana GIS Clearinghouse, 2009
Produced water sample locations	Fig. 7-1	WOGCC, Produced water database, 2009
Springs	Plate IV	Stafford and Gracias, 2009
SWAP locations	Fig 8-3	Modified from Trihydro Corporation, 2004
Tribal groundwater wells	Plate IV, Figs. 8-2, 8-4, 8-6, 8-7, 8-8, 8-10	Modified from Joint Tribal Water Engineer (TWE) of the Wind River Indian Reservation groundwater database of 1985, received through the Wyoming State Engineer's Office
WOGCC coalbed natural gas wells	Plates IV, X	Modified from WOGCC coal bed methane wells database of 2009

WOGCC potential groundwater development areas	Plate X	Digitized from BRS, Inc., 2003e
WSEO groundwater permits	Plates IV, X, Figs. 8-1 to 8-10	Modified from Wyoming State Engineer's Office, e-Permit database of 2009

POTENTIAL GROUNDWATER CONTAMINANTS

Abandoned mine sites	Fig. 5-8	Created from WDEQ Abandoned Mine Land table of 2010
Active coal mine	Fig. 5-7	Modified from WSGS active coal mine GIS dataset of 2003
Active and permanently abaondoned injector and disposal wells associated with oil and gas	Fig. 5-3	Modified from WOGCC well header data as of 2009
Active large and small mine permits	Fig. 5-7	Modified from WDEQ Land Quality Division (LQD) large and small active mine permit tables of 2010
Active limited mine operations (ETs)	Fig. 5-7	Modified from WDEQ LQD limited mine operation GIS dataset of 2010
Active storage tanks	Fig. 5-6	Modified from WDEQ Solid and Hazardous Waste Division (SHWD) storage tank table of 2009
Active Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Fig. 5-4	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2009
Commercial oil and gas disposal pits	Fig. 5-6	WDEQ/WQD commercial oil and gas disposal pit GIS dataset of 2009
Concentrated Animal Feeding Operations (CAFOs)	Fig. 5-5	Modified from WDEQ/WQD CAFO table of 2009
Known contaminated groundwater areas	Fig. 5-6	WDEQ/WQD Groundwater Program known contaminated areas GIS dataset of 2009
Oil and gas fields	Fig. 5-3	De Bruin, 2007
Orphan sites	Fig. 5-6	Modified from WDEQ SHWD orphan site GIS dataset of 2009
Pipelines	Fig. 5-3	Wyoming Pipeline Authority pipeline GIS dataset of 2007
Solid and hazardous waste facilities	Fig. 5-5	Modified from WDEQ SHWD solid and hazardous waste facilities table of 2009
Underground Injection Control (UIC) Class I and V wells	Fig. 5-4	Modified from WDEQ/WQD UIC GIS dataset of 2009
Voluntary Remediation Program (VRP) sites	Fig. 5-6	Modified from WDEQ SHWD VRP tables and GIS datasets of 2009
WSGS mines, pits, mills, and plants	Fig. 5-9	Harris, 2004

ISOPACHS

Isopachs, Bighorn Basin	Plate VIII	Modified from Thomas, 1965; Parker, 1986; and Parker and Jones, 1986

Isopachs, Wind River Basin	Plate VII	Modified from Keefer and Van Liew, 1966, and Hogle and Jones, 1992
Subsurface extents, Wind River and Bighorn Basins	Plates VII and VIII	Estimated by Scott Quillinan, WSGS, 2010
Well control points, Bighorn Basin	Plate VIII	Digitized from Parker, 1986, and Parker and Jones, 1986
Well control points, Wind River Basin	Plate VII	Digitized from Keefer and Van Liew, 1966, and Hogle and Jones, 1992
Volcanic rocks	Plate VIII	Selected by Scott Quillinan and Nikolaus Gribb, WSGS
Base Data		
Continental divide	Fig. 3-2	Modified from U.S. Department of Agriculture, 2002
Elevation and hillshade	Plates I, IV, Fig. 3-2, 3-3, 5-1, 5-2, 6-1 to 6-6	Modified from U.S. Geological Survey, 1999a
Lakes and rivers	Fig.1-1, 3-2, 8-1 to 8-10	U.S. Geological Survey, 1999b, and Stafford and Gracias, 2009
Montana counties	Plates I, IV, VII, VIII, X, Figs. 3-1 to 3-3, 4-1, 5-1 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	Modified from Montana Dept of Administration, 2008
Montana townships	Plates, I, IV, X, Figs. 3-1, 4-1, 5-2 to 5-9, 7-1, 8-1 to 8-10	Modified from U.S. Bureau of Land Management, 2006
Mountain peaks	Fig 3-2	WSGS, unplublished mountain peaks GIS dataset of 2008
Wind River Reservation boundary	Plates I, IV, VII, VIII, X, Figs. 3-1 to 3-3, 4-1, 5-1 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	U.S. Census Bureau, 1997
Wyoming and Montana highways	Plates, I, IV, X, Fig 3-1	ESRI® Data and Maps, 2006a
Wyoming and Montana state boundaries	Plates I, IV, VII, VIII, X, Figs. 3-1 to 3-3, 4-1, 5-1 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	Modified from Stoeser, Green, et al., 2005
Wyoming and Montana towns	Plates, I, IV, X, Figs. 1-1, 3-1, 3-2, 8-1, 8-3	ESRI® Data and Maps, 2006b
Wyoming counties	Plates I, IV, VII, VIII, X, Figs. 3-1 to 3-3, 4-1, 5-1 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	Modified from Spatial Data and Visualzation Center, 1993
Wyoming townships	Plates, I, IV, VII, VIII, X, Figs. 3-1, 4-1, 5-2 to 5-9, 7-1, 8-1 to 8-10	Modified from Premier Data Services, 2003–2008
Yellowstone National Park boundary	Plates I, IV, VII, VIII, X, Figs. 3-1 to 3-3, 4-1, 5-1, 5-2, 5-4 to 5-9, 6-1 to 6-6, 7-1, 8-1 to 8-10	Spatial Analysis Center, Yellowstone National Park, 1995

Appendix D1

Summary of current aquifer uses and development potential – Wind River Basin, Wyoming

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
Cenozoic					
7.1.1 Quaternary unconsolidated-deposit aquifers	alluvium, colluvium, terrace, dune sand, and glacial deposits	Major Aquifer – Alluvial	domestic, stock, public supply from shallow wells	variable – can be high in areas – mostly same as current uses – may be complicated by interconnection to surface water	As much as 200 but generally less than 50 feet of sand and gravel interbedded with silt and clay with some coarser cobble and boulder deposits – Small areal extent and limited continuity – Can be highly productive locally where saturated thicknesses is large and coarse-grained deposits predominate – Significant source of water primarily in alluvium near larger streams and rivers where recharge from surface water and irrigation predominates – Water quality is variable and commonly reflects source of recharge – Highly vulnerable to surface/near-surface sources of contamination
7.1.2 Split Rock aquifer	Split Rock Formation	Major Aquifer – Sandstone (primarily in Platte River drainage basin)	mostly stock in WRB	limited extent limits development potential	Limited extent occurs only in SE WRB – Fine-grained sandstone up to 650 ft thick – Some tuff, bentonite, arkose, and conglomerate – Good intergranular permeability and porosity – Mostly unconfined – Well yields vary widely based on permeability, depth of penetration, and well construction – Fractures may increase permeability locally – Water quality information is not available
7.1.3 White River aquifer	White River Formation	Marginal Aquifer (primarily in Platte River drainage basin)	limited extent in WRB	limited extent limits development potential	Limited extent occurs only in SE WRB – Fine- to medium-grained sandstone up to 930 ft thick – Some tuff and conglomerate – Reported good intergranular permeability and porosity is unconfirmed but may support development in limited areas of occurrence – Water quality variable and generally suitable for most uses including domestic but based on limited information
7.1.4 Aycross–Wagon Bed confining unit	Tepee Trail, Aycross, and Wagon Bed Formations	Confining Unit[1,2,3]		not significant	Limited extent occurs only in NW and SE WRB – Although not considered aquifers the Tepee Trail and Wagon Bed Formations can yield small quantities (less than 10 gal/min) of water to springs and shallow wells in outcrop areas – No water quality samples available from the Tepee Trail and Aycross Formations – Water quality in Wagon bed Formation is variable and generally suitable for most uses including domestic but based on limited information
7.1.5 Wind River aquifer	Wind River Formation	Major Aquifer – Sandstone	domestic, stock, irrigation, industrial, and public supply	high - same as current uses - especially widespread area for domestic and stock supply	Present at or near land surface in the interior basin – Up to 5,000 ft of interbedded lenticular claystone, shale, siltstone, conglomerate, lenticular beds of fine- to coarse-grained sandstone of variable thickness and lateral continuity; small amounts of bentonite, tuff, and limestone – Coarser deposits more abundant along the basin margins, closer to sediment sources – Many coarse-grained sandstone and conglomerate beds are very well sorted, loosely cemented, very porous, and permeable; some can function as separate aquifers – Primarily intergranular permeability can be enhanced by fractures in deformed areas – Three distinct facies: lower and upper fine-grained, and middle coarse-grained sequences (most productive); wells greater than 100 ft deep generally completed in confined and shallower wells in unconfined intervals respectively – Recharged from surface waters, irrigation, and precipitation – Vulnerable to surface/near-surface sources of contamination – Water quality variable and generally suitable for most uses including domestic based on numerous samples

Continued.

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
	7.1.6 Indian Meadows confining unit	Indian Meadows Formation	Major Confining Unit		not significant	Up to 750 feet thick – Hydrogeological physical or water quality information is not available
	From this stratigraphic level hydrogeologic units become more deeply buried downdip from outcrop areas along surrounding mountain ranges – Generally too deep for viable water resources except in and near outcrop areas – Generally confined to semiconfined except in outcrop areas of relatively limited extent compared to units exposed interior basin areas – Recharged from precipitation and stream flow on outcrop areas – Water quality is variable (generally based on a declining number of environmental samples relative to produced water samples), better (often fresh) in outcrop areas, and declining (increasingly saline) with depth					
Fort Union–Lance aquifer	7.1.7 Fort Union aquifer	7.1.8 Fort Union Formation	Minor Aquifer	few water wells – mostly for stock use	marginal – same as current uses – mostly stock wells located in outcrop areas	Exposed at the surface around the perimeter of the basin, mostly deeply buried in the subsurface – Fort Union is composed of several thousand feet of highly variable interbedded conglomerate, fine- to coarse-grained sandstone, siltstone, mudstones, shale, carbonaceous shales, and coal – Lance is composed of up to 6000 feet of sandstone interbedded with shale, claystone, siltstone, and thin coal – Primarily intergranular permeability can be enhanced by fractures in deformed areas – Relatively low yield, variable hydrogeologic characteristics, variable water quality, and limited access to the aquifer preclude any substantial aquifer development – Water quality variable; unusable without treatment to marginally suitable for most uses including domestic based mostly on samples of produced water
	Mesozoic					
	7.1.7 Lance aquifer	7.1.9 Lance Formation	Minor Aquifer	few water wells – mostly oil and gas	marginal – same as current uses – mostly stock wells located in outcrop areas	
	7.1.10 Meeteetse–Lewis confining unit	Meeteetse Formation and Lewis Shale	Major Confining Unit		not significant	Meeteetse Formation consists of massive to thin bedded sandstone interbedded with shale, claystone, siltstone, mudstone, and occasional thin coal – Lewis Shale consists primarily of shale – Overall confining unit ranges from 500 to more than 1,750 feet thick – Water quality probably highly variable but few samples were available
	7.1.11 Mesaverde aquifer	Mesaverde Formation	Minor Aquifer	few water wells – mostly oil and gas	moderate – stock, domestic, and limited public supply – Teapot Sandstone likely best potential[2]	500 to 2,200 feet of variable sequence of massive lenticular fine- to coarse-grained sandstone, carbonaceous shale, and coal – Composed of four members: Teapot Sandstone, unnamed middle member (siltstone, shale, carbonaceous shale, thin-bedded discontinuous sandstone), Parkman Sandstone, Fales Sandstone – Sandstones commonly function as distinct subaquifers – Intergranular permeability enhanced locally by fractures – Variable, generally poor water quality precludes many uses without treatment
	7.1.12 Cody confining unit	Cody Shale	Major Confining Unit		not significant	3,250 to 5,500 feet of marine shale with minor sandstone and siltstone – Sandstones and fractured zones can yield small quantities of water locally – Poor water quality limits most uses without treatment

Continued.

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.1.13 Lower and Middle Mesozoic aquifers and c.u.s	7.1.13.1 Frontier aquifer	Frontier Formation	Minor Aquifer	stock and domestic, mostly where exposed along the Wind River Range	marginal – same as current uses – stock and domestic wells in outcrop areas	700 to 1,200 feet of alternating sequence of very fine- to medium-grained sandstone and shale in three stratigraphic members: upper Wall Creek Sandstone and middle Emigrant Gap (aquifer part) and lower Belle Fourche (confining unit) – Alternating sandstone and shale strata creates a series of subaquifers – Good recharge potential in the SW WRB – Highly variable, generally poor water quality precludes many uses without treatment.
	7.1.13.2 Mowry–Thermopolis confining unit and Muddy Sandstone aquifer	Mowry Shale, Muddy Sandstone, Thermopolis Shale	Major Confining Unit Minor Aquifer Major Confining Unit	very few water wells – mostly oil and gas	minor – limited to low-yield wells along the basin margin outcrop areas	Mowry Shale is composed of siliceous shale and bentonite ranging from 395 to 560 feet thick – Thermopolis Shale is composed of shale and siltstone ranging from about 100 to 175 feet thick – Muddy aquifer is a massive sandstone with interbedded mudstone 20 to 134 feet thick – Intergranular permeability is generally low due to cementation and silty matrix; locally enhanced by fractures – Water quality variable and generally poor but based on few samples (mostly produced water)
	7.1.13.5 Cloverly aquifer	Cloverly Formation	Minor Aquifer	domestic and stock in outcrop areas	mostly marginal – same as current uses – domestic and stock wells located in outcrop areas, better along Wind River Range[2]	200 to 300 feet thick, includes three units: upper Dakota Sandstone interbedded with lenticular cherty pebble conglomerate and thin variegated shale, a middle Fuson Shale, and lower basal fine- to coarse-grained Lakota Sandstone – Sandstones are subaquifers separated by leaky middle shale – Permeability is mostly secondary fractures highest in structurally deformed areas – Excellent recharge potential along the Wind River Range – Water quality is variable (based on few samples) generally fresh in outcrop areas and declining with depth (based on produced water samples)

Continued.

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.1.13 Lower and Middle Mesozoic aquifers and c.u.s	7.1.13.6 Morrison confining unit	Morrison Formation	Confining Unit and Minor Aquifer[1,2,3]	possibly stock and domestic in outcrop areas	minor – stock and domestic wells located in outcrop areas	300 to 570 feet of variegated claystone and shale with thin interbedded lenticular fine- to medium-grained friable sandstone – Interbedded sandstone beds may yield small quantities of water for domestic or stock use – Limited potential for development because of limited outcrop area and small yields – Water quality is variable (based on few samples) generally better in outcrop areas and declining with depth
	7.1.13.7 Sundance–Nugget aquifer	Sundance Formation Nugget Sandstone	Minor Aquifer Major Aquifer – Sandstone	possibly stock and domestic in outcrop areas	very limited by small outcrop area and small yields for stock or domestic use	200 to 900 feet thick – Sundance is composed of an upper fine- to coarse-grained sandstone with thin shale and limestone interbeds, and a basal siltstone and sandstone grading downward into limestone, dolomite, and conglomerate – Nugget is composed of an upper fine- to medium-grained sandstone, a basal siltstone, mudstone, limestone, and thin to massive very fine-grained sandstone – Intergranular permeability is locally enhanced by fractures – Water quality is variable and generally poor precluding most uses without treatment except in outcrop areas based on few samples
	7.1.13.8 Gypsum Spring confining unit	Gypsum Spring Formation	Marginal Aquifer and Confining Unit[1,2,3]	no wells noted in WRB	not significant	Up to 230 feet of upper alternating siltstone, shale, limestone, dolomite, and gypsum, and basal sandy siltstone and silty shale – Present only in the western two-thirds of the WRB – Very limited outcrop area and accessibility – Poor water quality likely
	7.1.13.9 Chugwater–Dinwoody aquifer and confining unit	Chugwater Group or Formation and Dinwoody Formation	Marginal Aquifer & Confining Unit[1,2,3]		marginal – for domestic and stock wells in outcrop areas	Water quality for all members of the group is variable (based on few samples) generally fresh in outcrop areas and declining with depth (based on produced water samples) to generally unusable without treatment
Paleozoic						
	7.1.14 Goose Egg–Phosphoria aquifer and confining unit	Phosphoria / Park City Formations and Goose Egg Formation	Minor Aquifer	limited to low yield wells along in and near outcrop areas	minor – stock and domestic wells in outcrop areas	Phosphoria/Park City is up to 300 feet of interbedded dolomite, chert, limestone, siltstone, and fine-grained sandstone with phosphate beds/lenses and minor shale – Goose Egg is up to 300 feet of shale, siltstone, limestone, and gypsum – Complex intertonguing between facies creates small permeable zones that can function as separate confined aquifers/subaquifers and can function as both a confining unit and an aquifer – Subaquifers can be hydraulically connected by faults and fractures – Intergranular permeability is generally small, but locally enhanced by fractures especially near the basin margins – Water quality is variable (based on few samples) generally fresh in outcrop areas and declining with depth (based on produced water samples) to generally unusable without treatment

Continued.

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.1.15 Paleozoic aquifer system	7.1.15.1 Tensleep aquifer	Tensleep Sandstone	Major Aquifer – Limestone	domestic, public supply, industrial, and irrigation (rare)	high – for many uses – primarily around the basin perimeter where fractures enhance permeability and not too deeply buried	200 to 600 feet of massive to cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica with thin layers of chert, limestone, and dolomite – One of the most productive aquifers in the basin with the uppermost 200 feet most productive – Porosity and permeability is primarily intergranular dependent on the amount of secondary cementation and re-crystallization, both increasing with depth – Fractures and solution processes (in carbonate-rich zones) significantly enhances intergranular permeability in deformed areas where the most productive wells are located – Water quality is generally good to excellent in and near (downdip of) outcrop areas, especially where groundwater circulation is vigorous, and declines downdip into the basin becoming unusable without treatment
	7.1.15.2 Amsden aquifer	Amsden Formation	Marginal Aquifer	very few wells – essentially no development per better potential in other, often shallower, | aquifers	marginal – except where integrated with adjacent aquifers – same rationale as current uses	Composed of two stratigraphic sequences up to 400 feet thick – An upper nonresistant shale, dense dolomite, thin cherty limestone, and thin, resistant, fine-grained sandstone; and a basal Darwin Sandstone Member of fine- to medium-grained, crossbedded to massive, friable, porous, sandstone – The permeable parts of the Amsden Formation comprise the aquifer – Permeability of the Darwin is due to bedding plane joints and partings – Permeability of entire unit enhanced locally by fractures – Only one moderately saline produced water sample
	7.1.15.3 Madison aquifer	Madison Limestone	Major Aquifer – Limestone	domestic, commercial, stock, public supply, industrial, and rare irrigation	high – for many uses – primarily around the basin perimeter where shallow and solution-enhanced fracture permeability dominates	Composed of an upper 100 feet of predominantly thin to massive limestone and dolomite, and a lower 500 to 600 feet of predominantly massive to thin-bedded crystalline limestone and dolomitic limestone – Permeability is primarily secondary solution-enhanced fractures, joints, and caverns mostly in the upper 1/3 of the aquifer – Primary permeability is insignificant in the dense, finely crystalline carbonates – Most productive hydrogeologic unit in the basin where solution-enhanced fracture permeability dominates – Most wells are located along the basin margin where structurally deformed and exposed or present at relatively shallow depths – water quality is generally good to excellent in and near (downdip of) outcrop areas, especially where groundwater circulation is vigorous within highly permeable solution-enhanced fractures, and declines downdip into the basin eventually becoming unusable without treatment
	7.1.15.4 Darby aquifer	Darby Formation	Marginal – Minor Aquifer[1,2,3]	few if any wells – no quantitative hydrogeologic or water quality information available	marginal – except where integrated with adjacent aquifers – same rationale as current uses	Present only in the western half of the WRB, is composed of up to 200 feet of resistant dolomite, siltstone, and shale – Likely functions as an aquifer only in areas with substantial secondary fracture permeability development – No water quality information but likely similar to Madison & Bighorn aquifers especially where integrated

Continued.

Summary of current aquifer uses and development potential – Wind River Basin (Section 7.1)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.1.15 cont.	7.1.15.5 Bighorn aquifer	Bighorn Dolomite	Major Aquifer – Limestone	few wells – very limited quantitative hydrogeologic or water quality information available	moderate – especially where integrated with adjacent aquifers – same rationale as current uses	Composed of up to 300 feet of the upper Leigh Dolomite Member of dense, thin-bedded to massive dolomite, and the basal Lander Sandstone Member of fine- to medium-grained sandstone – Permeability in the Lander Sandstone Member is likely both primary (intergranular) and secondary (joints and fractures), permeability in the Leigh Dolomite is secondary – Little quantitative hydrogeologic or water quality information is available for the WRB (few wells) – Water from limited springs samples was fresh
	7.1.16 Gallatin–Gros Ventre confining unit	Gallatin Limestone and Gros Ventre Formation	Minor Aquifer/ Confining Unit[1,2,3]	few if any wells – very limited quantitative hydrogeologic or water quality information available	probably not significant	Gallatin ranges up to 450 feet of thinly-bedded to massive glauconitic and oolitic limestone with interbedded shale, silty shale, and thin sandstone beds and Gros Ventre ranges up to 700 feet of limestone, shale, calcareous shale, with a flat-pebble conglomerate at the base of the formation – Although generally considered confining units both may yield small quantities of water to wells and springs especially from joints and fractures – Very little quantitative hydrogeologic or water quality information is available for the WRB
	7.1.17 Flathead aquifer	Flathead Sandstone	Major Aquifer – Limestone	Although a good potential source of groundwater for may many uses, essentially undeveloped due to limited and generally inaccessible outcrop areas and very deep burial in most of the WRB		50 to 200 feet of fine-to medium-grained arkosic and quartzitic sandstone with some conglomerate and arkose in the lower part – Primary permeability is intergranular, enhanced along partings between bedding planes and areas of local fracturing – Where confined commonly under high artesian pressure and will flow at ground surface – Little quantitative hydrogeologic or water quality information is available for the WRB (few wells) – Water from limited springs samples was fresh
Precambrian						
	7.1.18 Precambrian basal confining unit	Precambrian Crystalline Basement Complex	Major Confining Unit and Minor Surficial Aquifer in outcrop areas	local domestic, possibly stock	same as current – domestic and stock	Nonporous igneous and metamorphic rocks function as the basal confinement for the WRB groundwater basin – In outcrop areas shallow wells are developed locally for domestic use – Permeability is from weathered regolith, and jointed and fractured crystalline bedrock – Little quantitative hydrogeologic and water quality information is available – Water quality from spring samples is very fresh and based on shallow depth of circulation, high rate of circulation, high rate of recharge, lack of soluble minerals. and low surface area of the aquifer matrix (fractures) good to excellent water quality is probably common

Sources:
[1]Chapter 7.0 (this study)
[2]Plate II (this study)
[3]Plate IV (this study)
[4]WWDC (2007) and Section 5.3 (this study)

Appendix D2

Summary of current aquifer uses and development potential – Bighorn Basin, Wyoming (Section 7.2)

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
	Cenozoic					
	7.2.1 Quaternary unconsolidated-deposit aquifers	alluvium, colluvium, terrace landslide, and glacial deposits	Major Aquifer – Alluvial	domestic, stock, irrigation, public supply from shallow wells	variable – can be high in areas – mostly same as current uses – maybe complicated by interconnection to surface water	As much as 100 but generally less than 30 feet of sand and gravel interbedded with silt and clay with some coarser cobble and boulder deposits (near mountainous source areas) – Small areal extent and limited continuity – Can be highly productive locally where saturated thicknesses is large and coarse-grained deposits predominate – significant source of water primarily in alluvium near larger streams and rivers where recharge from surface water and irrigation predominates – Water quality is variable and commonly reflects source of recharge – Highly vulnerable to surface/near-surface sources of contamination
	7.2.2 White River aquifer	White River Formation	Marginal Aquifer (primarily in Platte River drainage basin)	no reported use in BHB	limited extent limits development potential	Limited extent present only as erosional remnants in the Bighorn Mountains – No quantitative physical and groundwater quality characteristics available – See WRB section of this report
	7.2.2 Wagon Bed confining unit	Wagon Bed Formation	Confining Unit/ Marginal Aquifer[1,2,3]	no reported use in BHB	limited extent – not significant	Limited extent present only in the Owl Creek Mountains – No quantitative physical and groundwater quality characteristics available – See WRB section of this report
7.2.3 cont.	7.2.3.1 Willwood aquifer	Willwood Formation	Minor Aquifer	stock and domestic	same as current uses – stock and domestic	Aerially extensive and exposed throughout the central part of the BHB – 800 to 5,000 feet of fine- to coarse-grained sheet or channel sandstones interbedded with shale and other fine-grained strata, with some local lenses of conglomerate and coal – Sandstones vary widely in geometry and thickness – Channel (shoestring) sandstones are very narrow and generally less than 10 feet thick – The proportion of sandstone to fine-grained strata varies substantially by location from 3 to 88 percent and averaging approximately 25 percent – Water-table conditions may exist in the shallowest sandstones – Well productivity dependent on the number of beds and total thickness of sandstone penetrated – Median spring and well yields are less than 10 gal/min – Water quality varies widely and is susceptible to contamination from surface sources – Nearly indistinguishable from the Fort Union on physical characteristics
	From this stratigraphic level hydrogeologic units become more deeply buried downdip from outcrop areas along surrounding mountain ranges – Generally too deep for viable water resources except in and near outcrop areas – Generally confined to semiconfined except in outcrop areas of relatively limited extent compared to units exposed interior basin areas – Recharged from precipitation and stream flow on outcrop areas – Water quality is variable (generally based on a declining number of environmental samples relative to produced water samples), better (often fresh) in outcrop areas, and declining (increasingly saline) with depth					

Continued.

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.2.3 Lower Tertiary/Upper Cretaceous aquifer system	7.2.3.1 Fort Union aquifer	Fort Union Formation	Major Aquifer – Sandstone	stock and domestic	same as current uses – stock and domestic	Aerially extensive and exposed primarily along the margins of the BHB – 1,000 to 11,500 feet of fine- to coarse-grained sheet or channel sandstones interbedded with shale and other fine-grained strata, with some local lenses of conglomerate and coal – Sandstones vary widely in geometry and thickness – Channel (shoestring) sandstones are very narrow and generally less than 10 feet thick – The proportion of sandstone to fine-grained strata varies substantially by location from 3 to 88 percent and averaging approximately 25 percent – Water-table conditions may exist in the shallowest sandstones – Well productivity dependent on the number of beds and total thickness of sandstone penetrated – Median spring and well yields are less than 10 gal/min – Water quality varies widely and is susceptible to contamination from surface sources – Nearly indistinguishable from the Fort Union on physical characteristics
	Mesozoic					
	7.2.3.4 Lance aquifer	Lance Formation	Major Aquifer	stock, domestic, and limited public supply	marginal – same as current uses – mostly stock and domestic wells located in outcrop areas	Exposed at the surface around the perimeter of the basin, mostly deeply buried in the subsurface – 800 to 1,800 ft of sandstone interbedded with shale, claystone, siltstone, and thin coal – Lenticular sandstones are often confined by fine-grained lithologies resulting in a sequence of subaquifers – Primarily intergranular permeability can be enhanced by fractures in deformed areas – Relatively low yield, variable hydrogeologic characteristics, variable water quality, and limited access to the aquifer preclude any substantial aquifer development – Water quality variable; unusable without treatment to marginally suitable for most uses including domestic
	7.2.3.5 Meeteetse aquifer and confining unit	Meeteetse Formation and Lewis Shale	Major Confining Unit and Minor Aquifer[1,2,3]	stock and domestic	marginal – stock and domestic	650 to 1,200 feet of lenticular clayey to silty fine-grained poorly indurated sandstone interbedded with shale, claystone, siltstone, bentonite, and occasional thin coal – Lenticular sandstones are commonly confined by fine-grained lithologies resulting in a sequence of subaquifers – Where present, the Lewis Shale is interbedded with the Meeteetse Formation and functions as a confining unit – Considered both an aquifer and confining unit – Poor water quality precludes most uses without treatment.
	7.2.3.6 Mesaverde aquifer	Mesaverde Formation	Major Aquifer – Sandstone	few water wells – mostly oil and gas	moderate – stock, domestic, and limited public supply – Teapot Sandstone likely best potential[2]	900 to 1,800 feet of variable sequence of massive lenticular fine- to coarse-grained sandstone, carbonaceous shale, and coal – Lenticular sandstones range from 5 to 40 feet thick are often confined by fine-grained lithologies resulting in a sequence of subaquifers – The lowermost part of the formation, the "Eagle Sandstone, consists of fine-grained sandstone and shaley sandstone – Intergranular permeability enhanced locally by fractures – Variable, generally poor water quality precludes most uses without treatment

Continued.

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
	7.2.4 Cody confining unit	Cody Shale	Major Confining Unit	possible stock and domestic	not significant	2,100 to 3,000 feet of upper gray sandy shale interbedded with shaley sandstone, and a lower dark gray marine shale with some glauconitic sandstone and thin beds of bentonite – Sandstones and fractured zones can yield small quantities of water locally – Poor water quality limits most uses without treatment
7.2.5 Lower and middle Mesozoic aquifers and confining units	7.2.5.1 Frontier aquifer	Frontier Formation	Minor Aquifer	stock and domestic, mostly where exposed in outcrop areas	marginal – same as current uses – stock and domestic wells located in outcrop areas	450 to 700 feet of lenticular fine- to medium-grained argillaceous sandstone and conglomeratic sandstone beds, interbedded with shale and lesser amounts of lignite and bentonite – Alternating lenticular sandstone interbedded with shale strata creates a series of subaquifers – Contains less than 50 percent sandstone – Highly variable, generally poor water quality precludes many uses without treatment
	7.2.5.2 Mowry–Thermopolis confining unit and Muddy Sandstone aquifer	Mowry Shale, Muddy Sandstone, Thermopolis Shale	Major Confining Unit and Minor Aquifer	very few (probably stock and domestic) water wells limited to basin margins – mostly oil and gas	minor – stock and domestic limited to low yield wells along the basin margin outcrop areas	Combined thickness over 700 feet – Mowry Shale: thin-bedded resistant/brittle shale with thin sandstone and bentonite beds in the upper part – Thermopolis Shale: soft black shale with sandy, silty, and bentonitic zones – Muddy aquifer (10 to 50 feet thick): includes massive sandstone interbedded with mudstone, siltstone, shale, bentonite, and some conglomerate – Water quality precludes most uses without treatment but based on few samples (mostly produced water)
	7.2.5.6 Cloverly aquifer	Cloverly Formation	Major Aquifer – Sandstone	domestic and stock in outcrop areas	mostly marginal – same as current uses – domestic and stock wells located in outcrop areas better along Wind River Range[2]	85 to 470 feet thick includes three units: upper Dakota Sandstone interbedded with silty sandstone and shale, a middle shale unit with uncommon sandstone lenses, and a lower lenticular Lakota Sandstone with conglomeratic sandstone with some siltstone and shale – Both sandstone units are permeable and 70 to 90 feet thick – Evaluated as a potential source of public supply in the northeastern BHB – Water quality is variable, generally fresh in outcrop areas and declining with depth
	7.2.5.7 Morrison confining unit and aquifer	Morrison Formation	Confining Unit and Minor Aquifer[1,2,3]	possibly stock and domestic in outcrop areas	limited by outcrop area and small yields – adequate only for stock and domestic use	75 to 300 feet of interbedded shale and mudstone, with minor silty fine-grained sandstone, limestone, and conglomerate lenses – The fine-grained strata are confining units, and the sandstones are commonly local aquifers or subaquifers – Water quality is variable (based on few samples) generally better in outcrop areas and declining with depth
	7.2.5.8 Sundance confining unit and aquifer	Sundance Formation	Marginal Aquifer[1,2,3]	possibly stock and domestic in outcrop areas	limited by small outcrop area and small yields for stock or domestic use	200 to 370 feet thick – Shale interbedded with glauconitic sandstone, siltstone, and limestone – Fine-grained strata are confining units, and the interbedded sandstones are commonly local aquifers or subaquifers – Water quality variable and generally poor precluding most uses without treatment except in outcrop areas based on few samples
7.2.5	7.2.5.9 Gypsum Spring confining unit and aquifer	Gypsum Spring Formation	Marginal Aquifer[1,2,3]	very few wells – possibly stock and domestic	very limited by small outcrop area and poor water quality	200 to 370 feet of siltstone, claystone, and shale with thin limestone and massive gypsum beds – Fine-grained strata are considered confining units and solution zones in gypsum beds are commonly local aquifers or subaquifers – Very limited outcrop area and accessibility – Likely poor water quality
	7.2.5.10 Nugget aquifer	Nugget Sandstone	Major Aquifer – Sandstone	No information was located discussing current uses, development potential, or physical and chemical characteristics of the Nugget aquifer in the BHB; however, this aquifer in the Wind River Basin is discussed in Section 7.1.11.6		

Continued.

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
	7.2.6 Chugwater–Dinwoody aquifer and confining unit	Chugwater Group or Formation, and Dinwoody Formation	Marginal Aquifer & Confining Unit[1,2,3]	although overall confining, can yield small quantities of water in outcrop areas	marginal – insignificant	450 to 1,200 feet thick of: Chugwater composed of fine-grained sandstone, siltstone, and shale with some thin lenticular beds of limestone and gypsum – Dinwoody includes silty shale and siltstone, with limestone, dolomite, and gypsum in the upper part – Water quality variable and generally poor based on few (mostly produced water) samples better in outcrop areas and declining with depth to generally unusable without treatment
				Paleozoic		
7.2.7 Paleozoic aquifer system	7.2.7.1 Goose Egg–Phosphoria aquifer and confining unit	Phosphoria/Park City Formations and Goose Egg Formation	Minor Aquifer	limited to few low-yield wells along in and near outcrop areas	minor – stock and domestic wells located in outcrop areas	The Park City is 25 to 325 feet of cherty dolomitic carbonates – The Goose Egg (Phosphoria equivalent) is 100 to 300 feet of evaporites including gypsiferous siltstone, mudstone, and silty shale – Overall low permeability but complex intertonguing between facies creates small permeable zones that can function as separate confined aquifers/subaquifers and can function as both a confining unit and an aquifer – Subaquifers can be hydraulically interconnected and hydraulically connected with the underlying Tensleep aquifer by faults and fractures – Intergranular permeability is generally small, but locally enhanced by fractures especially near the basin margins – Water quality is variable (based on few samples) generally fresh in outcrop areas and declining with depth (based on produced water samples) to generally unusable without treatment
	7.2.7.4 Tensleep aquifer	Tensleep Sandstone and Ranchester Limestone Member of the Amsden Formation	Major Aquifer – Limestone	domestic, public supply, industrial, and irrigation (rare) primarily along the eastern margin outcrops or at shallow depths	high – for many uses – primarily around the basin perimeter where fractures enhance permeability and not too deeply buried	The Tensleep is cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica with cherty dolomite in the upper part and discontinuous limestone and dolomite in the lower part – The Ranchester is primarily limestone generally not permeable except where dolomitized – One of the most productive aquifers in the basin – Porosity and permeability is primarily intergranular dependent on the amount of secondary cementation and re-crystallization, both increasing with depth – Fractures and solution processes (in carbonate-rich zones) significantly enhances intergranular permeability in deformed areas where the most productive wells are located – Water quality is generally good to excellent in and near (downdip of) outcrop areas, especially where groundwater circulation is vigorous, and declines downdip into the basin becoming unusable without treatment
	7.2.7.5 Amsden confining unit	Amsden Formation	Marginal Aquifer and Confining Unit[1,2,3]	no development per better potential in other, often shallower Pz aquifers	insignificant – except where integrated with adjacent aquifers	120 to 300 feet of Ranchester Limestone, Horseshoe Shale, and Darwin Sandstone – Water quality variable and generally poor based only on produced water samples

Continued.

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.2.7 Paleozoic aquifer system – continued	7.2.7.6 Madison–Bighorn aquifer	Darwin Sandstone (Member of the Amsden Fm.), Madison Limestone, Darby, Three Forks, and Jefferson Formations, and Bighorn Dolomite	Major Aquifer – Limestone	domestic, commercial, stock, public supply for numerous communities and irrigation along the eastern margin outcrops or at shallow depths	high – for many uses – primarily around the basin perimeter where shallow and solution-enhanced fracture permeability dominates	The most important aquifer system in the BHB – Predominantly thick-bedded limestone and dolomite with minor interbedded siltstone and some chert – Hydrogeologic units of the aquifer system are hydraulically connected by solution enlarged joints and fractures – Thickness is highly variable and depends on the thickness and extent of hydraulic connection – Faulting and fracturing also provide hydraulic connection with overlying and underlying hydrogeologic units at some locations – Primary permeability is insignificant in the dense, finely crystalline carbonates – Permeability is mostly secondary fractures, joints, and caverns attributed folding and faulting of brittle carbonates solution-enhanced by groundwater flow – Permeability decreases basinward due to less deformation, decreasing solution enhancement of fractures (lower hydraulic gradient & less flow), re-precipitation of cements, and decreasing carbonate solubility as temperatures increase – Most productive hydrogeologic unit in the basin where solution-enhanced fracture permeability dominates – Most wells are located along the basin margin where structurally deformed and exposed or present at relatively shallow depths – Some wells yield large and dependable supplies of potable water – Water quality is generally good to excellent in and near (downdip of) outcrop areas, especially where groundwater circulation is vigorous within highly permeable solution-enhanced fractures, and declines downdip into the basin eventually becoming unusable without treatment – Water quality also reflects mixing between different hydrogeologic units
	7.2.8 Gallatin–Gros Ventre confining unit	Gallatin Limestone and Gros Ventre Formation	Minor Aquifer and Confining Unit[1,2,3]	few if any wells – very limited quantitative hydrogeologic or water quality information available	probably not significant	800 to 1,200 feet of Gallatin: glauconitic gray-green shale and pebbly limestone with minor interbedded sandstone, and Gros Ventre: glauconitic and sandy limestone with interbedded shale, sandy limestone, and minor interbedded limey sandstone – Although generally considered confining units both may yield small quantities of water to wells and springs especially from interbedded limestones and sandstones – Very little quantitative hydrogeologic or water quality information is available for the BHB
	7.2.9 Flathead aquifer	Flathead Sandstone	Major Aquifer – Limestone	stock and irrigation along the east margin of the BHB, where outcropping or at shallow depths	Same as current – potentially very good source of groundwater for development but limited by accessibility to outcrop areas and very deep burial in most of the BHB	absent in the northeastern BHB – 100 to 200 feet of fine- to medium-grained arkosic and quartzitic sandstone with some interbedded shale in the upper part – primary permeability is intergranular but secondary permeability is present as a result of fracturing near folds and faults – where confined commonly under high artesian pressure and will flow at ground surface – flowing wells located along the mountain-basin margin can yield large and dependable supplies of potable water – water from limited environmental samples was generally fresh

Continued.

Summary of current aquifer uses and development potential – Bighorn Basin (Section 7.2)

	Section[1]/ hydrogeologic unit	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
Precambrian						
	7.2.10 Precambrian basal confining unit	Precambrian Crystalline Basement Complex	Major Confining Unit and Minor Surficial Aquifer in outcrop areas	local domestic, possibly stock	same as current – domestic and stock	Nonporous igneous and metamorphic rocks function as the basal confinement for the WRB groundwater basin – In outcrop areas shallow wells are developed locally for domestic use – Permeability is from weathered regolith, and jointed and fractured crystalline bedrock – Little quantitative hydrogeologic and water quality information is available – Water quality from spring samples is very fresh and based on shallow depth of circulation, high rate of circulation, high rate of recharge, lack of soluble minerals and low surface area of the aquifer matrix (fractures), good to excellent water quality is probably common

Sources:
[1]Chapter 7.0 (this study)
[2]Plate III (this study)
[3]Plate IV (this study)
[4]WWDC (2007) and Section 5.3 (this study)

Appendix D3

Summary of current aquifer uses and development potential, Absaroka Range and Yellowstone Volcanic Area (AYV), Wyoming (Section 7.3)

Summary of current aquifer uses and development potential, Absaroka Range and Yellowstone Volcanic Area (AYV) (section 7.3)

Section / hydrogeologic unit[2]	Component geologic unit(s)[2]	Aquifer class[4]	Current uses	Development potential	Groundwater resources factors
7.3.1 Quaternary unconsolidated-deposit aquifers	Alluvium, landslide, lacustrine, hydrothermal, and glacial deposits	Major Aquifer – Alluvial	Nearly all development in AYV – domestic, small local public supply from shallow wells	variable – can be high in areas – mostly same as current uses – maybe complicated by interconnection to surface water	Alluvial, colluviual, lacustrine, and glacial deposits: Landslide deposits are saturated in some locations and yield water to springs – Locally overlie Quaternary and Tertiary volcanic-rock aquifers and likely are in direct hydraulic connection with them – Typically unconfined – Wells typically located close to and along streams or lakes – Commonly in hydraulic connection with and receive recharge from adjacent surface waters – Water quality variable and commonly reflects source of recharge and probably variable lithology – Highly vulnerable to surface/near surface sources of contamination
7.3.2 Quaternary and Tertiary volcanic-rock aquifers	7.3.2.1 Rhyolite flows, tuff, and intrusive igneous rocks	Marginal Aquifer	Few if any wells	essentially undeveloped but could yield adequate water for domestic, small local public supply and stock wells – little or no quantitative hydrogeologic information is available on development potential	Extrusive igneous rocks and beds of tuff and volcanic ash: Most investigations related to thermal waters and related features – May yield a few tens of gallons per minute per well from porous and fracture zones within rhyolitic ash, welded tuff, lava flows, breccias, and volcanic glass – Based primarily on samples from springs: similar to Quaternary unconsolidated aquifers – Water quality variable and commonly reflects source of recharge and probably variable lithology – Vulnerable to surface/near-surface sources of contamination
	7.3.2.2 Yellowstone Group				
	7.3.2.3 Absaroka Volcanic Supergroup				
7.3.3 Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers	7.3.3.1 Willwood aquifer	Willwood Formation	Minor Aquifer	Current use and development potential is limited – Mostly buried beneath Quaternary unconsolidated deposits and Quaternary and Tertiary volcanic rocks – Rarely utilized for water supply, and little information available describing their hydrogeologic characteristics within the AYV – Most water-quality data from produced-water samples from wells along the periphery of the AYV just outside of areas covered by volcanic rocks		
	7.3.3.2 Frontier aquifer	Frontier Formation	Minor Aquifer		
	7.3.3.3 Cloverly aquifer	Cloverly Formation	Major Aquifer – Sandstone		
	7.3.3.4 Morrison c.u. and aquifer	Morrison Formation	Confining Unit and Minor Aquifer[1,2,3]		
	7.3.3.5 Chugwater aquifer	Chugwater Group or Formation	Marginal Aquifer & Confining Unit[1,2,3]		
	7.3.3.6 Phosphoria aquifer and c.u.	Phosphoria Formation	Minor Aquifer		
	7.3.3.7 Tensleep aquifer	Tensleep Sandstone	Major Aquifer		
	7.3.3.8 Amsden c.u.	Amsden Formation	Marginal Aquifer[1,2,3]		
	7.3.3.9 Madison aquifer	Madison Limestone	Major Aquifer – Limestone		

Sources: [1]Chapter 7.0 (this study); [2]Plate III (this study); [3]Plate IV (this study); [4]WWDC (2007) and Section 5.3 (this study)

Appendix E1

Summary statistics for environmental water samples, Wind River Basin, Wyoming

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Cenozoic lithostratigraphic units							
Quaternary alluvial aquifers	pH (standard units)	6.8	7.4	7.6	8.0	11.4	120
	Specific conductance (µS/cm)	116	506	820	1,460	11,700	123
	Hardness (as $CaCO_3$)	3.0	189	320	570	2,500	107
	Calcium	0.88	52.0	78.0	138	600	110
	Magnesium	0.21	15.0	26.5	54.0	250	110
	Potassium	0.40	2.0	3.1	6.0	20.0	109
	Sodium-adsorption ratio (unitless)	0.10	0.60	1.4	2.5	45.0	105
	Sodium	2.0	20.0	53.0	121	1,100	110
	Alkalinity (as $CaCO_3$)	85.0	187	242	291	431	110
	Bromide	0.01	0.01	0.02	0.07	0.25	11
	Chloride	0.10	4.8	8.0	20.0	105	110
	Fluoride	0.10	0.20	0.43	0.81	1.6	108
	Silica	7.9	13.5	16.0	24.5	68.0	58
	Sulfate	2.8	45.4	151	595	2,600	110
	Total dissolved solids	102	299	539	1,170	4,630	110
	Ammonia (as N)	--	0.015	0.022	0.033	--	28
	Nitrate+nitrite (as N)	--	0.068	0.18	0.60	--	45
	Nitrate (as N)	--	0.19	0.81	1.9	--	65
	Nitrite (as N)	--	0.004	0.006	0.009	--	30
	Orthophosphate (as P)	--	0.008	0.014	0.020	--	26
	Phosphorus (as P)	--	0.004	0.008	0.016	--	11
	Phosphorus, unfiltered (as P)	--	0.010	0.020	0.030	--	11
	Aluminum	--	1.0	1.3	1.7	--	15
	Antimony	--	0.047	0.064	0.086	--	14
	Arsenic	--	0.35	0.51	0.76	--	21
	Barium	--	20.9	36.2	62.6	--	20
	Boron	--	64.3	144	295	--	44
	Cadmium	--	0.024	0.032	0.041	--	20
	Chromium	--	0.47	0.69	1.00	--	20
	Cobalt	--	0.43	1.1	1.9	--	11
	Copper	--	2.0	4.1	8.0	--	20
	Iron	--	13.0	63.3	420	--	61
	Iron, unfiltered	--	80.0	205	450	--	26
	Lead	--	<0.001	0.005	0.054	--	20
	Lithium	--	9.1	24.0	84.6	--	10
	Manganese	--	2.4	14.1	100	--	42

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers—Continued	Manganese, unfiltered	--	30.0	70.0	285	--	20
	Molybdenum	--	1.7	2.6	4.0	--	13
	Nickel	--	0.048	0.21	0.97	--	16
	Selenium	--	0.13	0.34	0.86	--	23
	Strontium	--	488	1,280	2,070	--	10
	Vanadium	--	0.51	0.91	1.6	--	12
	Zinc	--	1.6	4.6	20.0	--	19
	Gross beta radioactivity (picocuries per liter)	--	4.2	7.3	12.6	--	4
	Radon-222, unfiltered (picocuries per liter)	--	865	1,250	2,520	--	12
	Tritium, unfiltered (picocuries per liter)	--	20.2	40.6	41.6	--	3
	Uranium, natural	--	2.3	4.2	7.8	--	15
Quaternary terrace-deposit aquifers	pH (standard units)	6.4	7.5	7.7	8.1	8.7	18
	Specific conductance (µS/cm)	144	569	1,050	1,550	4,600	18
	Hardness (as $CaCO_3$)	7.0	88.8	258	505	2,200	16
	Calcium	1.0	60.3	69.5	133	486	14
	Magnesium	1.0	13.7	25.5	54.5	264	14
	Potassium	1.0	3.0	3.3	5.6	19.0	14
	Sodium-adsorption ratio (unitless)	0.20	0.60	2.5	5.9	130	12
	Sodium	4.0	32.1	125	250	740	16
	Alkalinity (as $CaCO_3$)	54.0	215	239	315	1,460	16
	Chloride	5.0	6.8	15.0	16.3	74.0	16
	Fluoride	0.12	0.23	0.42	1.3	8.8	14
	Silica	11.0	12.1	12.7	20.5	32.0	6
	Sulfate	2.0	67.7	149	616	2,790	16
	Total dissolved solids	85.0	463	746	1,440	4,400	16
	Ammonia (as N)	--	0.037	0.058	0.088	--	6
	Nitrate+nitrite (as N)	--	0.27	0.31	1.1	--	5
	Nitrate (as N)	--	0.049	0.56	3.4	--	14
	Boron	--	100	110	310	--	5
	Iron	--	60.0	145	190	--	10
	Manganese	--	5.6	24.9	50.0	--	6

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in Quaternary landslide deposits	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	171	--	--	--	--	1
	Hardness (as $CaCO_3$)	73.0	--	--	--	--	1
	Calcium	23.0	--	--	--	--	1
	Magnesium	3.8	--	--	--	--	1
	Potassium	1.3	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.30	--	--	--	--	1
	Sodium	6.4	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	84.0	--	--	--	--	1
	Chloride	0.10	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	29.0	--	--	--	--	1
	Sulfate	6.4	--	--	--	--	1
	Total dissolved solids	154	--	--	--	--	1
Aquifers in Quaternary dune sand (eolian) deposits	pH (standard units)	8.5	--	--	--	--	1
	Specific conductance (µS/cm)	1,240	--	--	--	--	1
	Hardness (as $CaCO_3$)	92.0	--	--	--	--	1
	Calcium	22.0	--	--	--	--	1
	Magnesium	8.6	--	--	--	--	1
	Potassium	4.5	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	11.0	--	--	--	--	1
	Sodium	230	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	175	--	--	--	--	1
	Chloride	8.1	--	--	--	--	1
	Fluoride	0.50	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	440	--	--	--	--	1
	Total dissolved solids	833	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary glacial-deposit aquifers	pH (standard units)	6.8	7.5	7.7	7.8	8.0	4
	Specific conductance (µS/cm)	165	326	409	451	490	4
	Hardness (as $CaCO_3$)	91.0	143	165	178	200	4
	Calcium	30.0	42.0	49.0	52.0	52.0	4
	Magnesium	4.0	8.5	10.0	11.5	16.0	4
	Potassium	1.0	1.8	2.1	2.3	2.4	4
	Sodium-adsorption ratio (unitless)	0.30	0.30	0.45	0.80	1.4	4
	Sodium	6.0	8.5	13.7	24.3	43.0	4
	Alkalinity (as $CaCO_3$)	86.0	94.3	118	144	157	4
	Chloride	4.0	4.2	8.1	12.5	14.0	4
	Fluoride	0.10	0.18	0.20	0.23	0.30	4
	Silica	11.0	--	--	--	19.0	2
	Sulfate	2.0	39.5	56.5	82.0	145	4
	Total dissolved solids	108	207	246	265	306	4
White River aquifer	pH (standard units)	6.9	7.2	7.5	7.8	7.9	6
	Specific conductance (µS/cm)	295	369	400	620	1,210	6
	Hardness (as $CaCO_3$)	20.0	--	210	--	270	3
	Calcium	7.8	40.2	54.0	64.5	87.0	4
	Magnesium	0.10	4.8	10.2	14.5	16.0	4
	Potassium	2.7	6.1	7.9	9.1	11.0	4
	Sodium-adsorption ratio (unitless)	0.10	--	0.60	--	7.7	3
	Sodium	4.3	18.3	51.0	102	170	4
	Alkalinity (as $CaCO_3$)	169	192	201	204	213	4
	Chloride	2.4	3.3	5.9	9.1	12.0	4
	Fluoride	0.30	0.30	0.50	0.72	0.78	4
	Silica	24.0	--	32.0	--	53.0	3
	Sulfate	2.0	17.8	66.5	185	411	4
	Total dissolved solids	247	265	334	504	823	4
	Nitrate+nitrite (as N)	--	0.25	0.30	1.5	--	3

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aycross-Wagon Bed confining unit	pH (standard units)	7.2	7.6	7.8	7.9	8.3	4
	Specific conductance (µS/cm)	330	354	436	615	930	4
	Hardness (as $CaCO_3$)	110	125	145	160	160	4
	Calcium	23.0	36.5	47.0	53.5	55.0	4
	Magnesium	5.6	6.2	6.5	8.1	13.0	4
	Potassium	1.5	2.8	3.4	3.6	3.6	4
	Sodium-adsorption ratio (unitless)	0.20	0.58	1.2	3.0	7.0	4
	Sodium	7.0	14.5	31.5	77.0	170	4
	Alkalinity (as $CaCO_3$)	135	153	170	229	374	4
	Chloride	3.6	5.0	6.5	8.2	10.0	4
	Fluoride	0.20	0.35	0.45	0.50	0.50	4
	Silica	18.0	22.5	28.0	35.5	46.0	4
	Sulfate	9.1	24.8	53.5	85.3	110	4
	Total dissolved solids	207	227	282	391	572	4
	Ammonia (as N)	--	0.020	0.030	0.040	--	4
Wind River aquifer	pH (standard units)	6.5	7.6	8.1	8.6	10.0	241
	Specific conductance (µS/cm)	350	742	1,120	1,760	6,300	263
	Hardness (as $CaCO_3$)	2.0	14.7	61.0	240	1,900	239
	Calcium	0.80	5.0	23.0	79.0	488	243
	Magnesium	0.02	1.0	2.0	17.0	190	240
	Potassium	0.10	1.0	2.0	4.4	30.0	242
	Sodium-adsorption ratio (unitless)	0.10	5.4	16.0	22.0	60.0	227
	Sodium	4.5	127	180	320	1,500	243
	Alkalinity (as $CaCO_3$)	18.0	124	163	210	1,220	243
	Chloride	3.0	9.3	16.0	34.5	693	243
	Fluoride	0.10	0.59	0.85	1.2	4.9	241
	Silica	1.3	8.3	10.0	13.0	39.0	140
	Sulfate	3.2	135	310	615	3,250	243
	Total dissolved solids	224	424	707	1,190	5,110	243
	Ammonia (as N)	--	0.030	0.050	0.14	--	39
	Nitrate+nitrite (as N)	--	0.002	0.024	0.79	--	88
	Nitrate (as N)	--	0.032	0.13	0.49	--	135
	Nitrite (as N)	--	0.001	0.003	0.007	--	39
	Orthophosphate (as P)	--	0.001	0.004	0.010	--	39
	Phosphorus, unfiltered (as P)	--	0.001	0.003	0.008	--	52
	Barium	--	7.5	9.2	11.3	--	7
	Boron	--	100	190	300	--	87

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wind River aquifer—Continued	Copper	--	1.0	1.5	2.3	--	7
	Iron	--	37.2	100	230	--	96
	Iron, unfiltered	--	60.0	205	1,400	--	78
	Manganese	--	1.7	7.0	29.5	--	60
	Manganese, unfiltered	--	12.0	25.0	90.0	--	24
	Selenium	--	0.073	0.36	1.8	--	25
	Gross alpha radioactivity (picocuries per liter)	--	0.74	1.6	3.1	--	7
	Gross beta radioactivity (picocuries per liter)	--	0.80	5.3	14.0	--	6
	Radon-222, unfiltered (picocuries per liter)	--	384	595	737	--	5
	Uranium, natural	--	0.059	0.54	52.0	--	6
Fort Union aquifer	pH (standard units)	8.1	--	8.4	--	8.8	3
	Specific conductance (µS/cm)	1,760	--	4,130	--	6,900	3
	Hardness (as $CaCO_3$)	28.0	--	77.3	--	140	3
	Calcium	8.3	--	21.2	--	23.0	3
	Magnesium	1.8	--	5.9	--	19.0	3
	Potassium	3.1	--	9.1	--	23.0	3
	Sodium-adsorption ratio (unitless)	32.0	--	--	--	56.0	2
	Sodium	387	--	827	--	1,500	3
	Alkalinity (as $CaCO_3$)	303	--	487	--	896	3
	Chloride	270	--	291	--	780	3
	Fluoride	1.1	--	--	--	2.6	2
	Silica	6.0	--	--	--	6.9	2
	Sulfate	1.5	--	4.0	--	3,100	3
	Total dissolved solids	1,010	--	2,200	--	5,110	3

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Mesozoic lithostratigraphic units							
Mesaverde aquifer	pH (standard units)	7.4	--	--	--	9.2	2
	Specific conductance (µS/cm)	1,800	--	--	--	2,140	2
	Hardness (as CaCO3)	7.0	--	--	--	580	2
	Calcium	1.3	--	--	--	140	2
	Magnesium	0.94	--	--	--	57.0	2
	Potassium	1.7	--	--	--	5.8	2
	Sodium-adsorption ratio (unitless)	4.1	--	--	--	72.0	2
	Sodium	230	--	--	--	440	2
	Alkalinity (as $CaCO_3$)	279	--	--	--	738	2
	Chloride	16.0	--	--	--	32.0	2
	Fluoride	0.50	--	--	--	9.3	2
	Silica	6.7	--	--	--	23.0	2
	Sulfate	180	--	--	--	810	2
	Total dissolved solids	1,100	--	--	--	1,470	2
Cody confining unit	pH (standard units)	7.1	7.5	7.8	8.3	8.9	10
	Specific conductance (µS/cm)	721	1,820	3,080	4,450	7,400	12
	Hardness (as $CaCO_3$)	16.0	224	700	1,250	1,900	11
	Calcium	2.9	47.0	134	289	380	11
	Magnesium	1.9	26.0	64.0	145	240	11
	Potassium	1.2	2.7	3.3	7.1	23.0	10
	Sodium-adsorption ratio (unitless)	0.60	6.4	13.0	17.5	44.0	11
	Sodium	37.0	250	535	700	1,390	11
	Alkalinity (as $CaCO_3$)	168	224	320	451	698	11
	Chloride	5.2	11.8	39.0	78.0	182	11
	Fluoride	0.10	0.60	0.77	1.1	2.5	11
	Silica	6.3	6.8	9.8	12.0	24.0	9
	Sulfate	89.0	634	983	2,310	4,300	11
	Total dissolved solids	451	1,240	1,750	3,870	6,850	11
	Ammonia (as N)	--	0.060	0.40	0.81	--	3
	Nitrate (as N)	--	0.52	6.5	37.7	--	4
	Phosphorus, unfiltered (as P)	--	0.007	0.010	0.010	--	5
	Boron	--	80.0	120	200	--	3
	Manganese	--	20.0	60.0	160	--	3

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer	pH (standard units)	6.7	7.6	7.8	8.1	8.6	17
	Specific conductance (µS/cm)	415	675	1,660	5,440	10,000	18
	Hardness (as $CaCO_3$)	6.0	130	240	460	1,800	17
	Calcium	2.2	32.5	57.0	117	409	19
	Magnesium	0.10	11.5	22.0	36.5	199	19
	Potassium	0.90	1.8	2.4	5.6	29.0	17
	Sodium-adsorption ratio (unitless)	0.10	1.7	8.2	22.0	100	17
	Sodium	5.1	57.0	276	820	2,690	19
	Alkalinity (as $CaCO_3$)	130	198	258	381	1,520	19
	Chloride	1.7	5.5	22.5	87.0	2,600	19
	Fluoride	0.40	0.73	0.95	1.4	2.3	18
	Silica	4.1	8.5	12.5	17.3	21.0	12
	Sulfate	7.7	86.5	294	955	5,800	19
	Total dissolved solids	280	473	1,170	3,030	9,060	19
	Nitrate+nitrite (as N)	--	0.065	0.12	0.30	--	9
	Nitrate (as N)	--	0.070	0.22	1.0	--	6
	Phosphorus, unfiltered (as P)	--	0.009	0.020	0.040	--	9
	Boron	--	70.0	950	2,000	--	5
	Iron	--	80.0	115	170	--	6
	Iron, unfiltered	--	38.8	64.3	145	--	4
	Manganese	--	8.5	16.3	155	--	4
Mowry confining unit	pH (standard units)	7.1	--	--	--	7.7	2
	Specific conductance (µS/cm)	702	--	--	--	970	2
	Hardness (as $CaCO_3$)	54.0	--	--	--	--	1
	Calcium	17.0	--	--	--	--	1
	Magnesium	2.9	--	--	--	--	1
	Potassium	1.9	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	11.0	--	--	--	--	1
	Sodium	180	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	130	--	--	--	--	1
	Chloride	5.7	--	--	--	--	1
	Fluoride	1.3	--	--	--	--	1
	Silica	20.0	--	--	--	--	1
	Sulfate	340	--	--	--	--	1
	Total dissolved solids	648	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Thermopolis confining unit	pH (standard units)	5.9	--	--	--	6.5	2
	Specific conductance (µS/cm)	355	--	--	--	800	2
	Hardness (as $CaCO_3$)	82.0	--	--	--	200	2
	Calcium	22.0	--	--	--	50.0	2
	Magnesium	6.5	--	--	--	18.0	2
	Potassium	0.90	--	--	--	2.8	2
	Sodium-adsorption ratio (unitless)	2.1	--	--	--	2.3	2
	Sodium	44.0	--	--	--	76.0	2
	Alkalinity (as $CaCO_3$)	4.0	--	--	--	113	2
	Chloride	4.4	--	--	--	10.0	2
	Fluoride	0.20	--	--	--	0.60	2
	Silica	10.0	--	--	--	22.0	2
	Sulfate	67.0	--	--	--	340	2
	Total dissolved solids	223	--	--	--	525	2
Cloverly aquifer	pH (standard units)	6.8	7.0	7.4	7.6	9.5	9
	Specific conductance (µS/cm)	445	694	1,180	1,600	2,240	9
	Hardness (as $CaCO_3$)	15.0	35.0	120	150	380	9
	Calcium	3.0	14.0	23.0	47.0	83.0	9
	Magnesium	0.70	5.7	8.2	21.3	41.0	8
	Potassium	1.0	2.7	4.5	5.6	11.0	9
	Sodium-adsorption ratio (unitless)	0.30	1.1	7.0	34.0	52.0	9
	Sodium	12.0	30.0	198	370	470	9
	Alkalinity (as $CaCO_3$)	76.0	153	236	281	573	9
	Chloride	6.0	7.9	10.0	15.0	82.0	9
	Fluoride	0.20	0.40	0.50	1.2	3.1	9
	Silica	8.8	12.0	14.0	17.5	27.0	6
	Sulfate	111	118	219	405	850	9
	Total dissolved solids	214	434	792	1,000	1,500	9
	Nitrate+nitrite (as N)	--	0.20	1.0	1.1	--	5
	Iron, unfiltered	--	60.0	140	750	--	5
	Manganese, unfiltered	--	50.0	120	360	--	3

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit	pH (standard units)	8.5	--	--	--	9.2	2
	Specific conductance (µS/cm)	1,380	--	--	--	2,400	2
	Hardness (as $CaCO_3$)	4.0	--	--	--	13.0	2
	Calcium	1.1	--	--	--	3.0	2
	Magnesium	0.31	--	--	--	1.3	2
	Potassium	0.50	--	--	--	1.2	2
	Sodium-adsorption ratio (unitless)	69.0	--	--	--	74.0	2
	Sodium	320	--	--	--	614	2
	Alkalinity (as $CaCO_3$)	343	--	--	--	411	2
	Chloride	8.2	--	--	--	26.0	2
	Fluoride	1.8	--	--	--	4.0	2
	Silica	7.9	--	--	--	9.6	2
	Sulfate	320	--	--	--	792	2
	Total dissolved solids	867	--	--	--	1,740	2
Sundance aquifer	pH (standard units)	8.0	--	--	--	--	1
	Specific conductance (µS/cm)	590	--	--	--	2,300	2
	Hardness (as $CaCO_3$)	300	--	--	--	--	1
	Calcium	75.0	--	--	--	--	1
	Magnesium	27.0	--	--	--	--	1
	Potassium	2.6	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.10	--	--	--	--	1
	Sodium	3.2	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	175	--	--	--	--	1
	Chloride	0.80	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	14.0	--	--	--	--	1
	Sulfate	100	--	--	--	--	1
	Total dissolved solids	331	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Gypsum Spring confining unit	pH (standard units)	7.9	--	7.9	--	8.3	3
	Specific conductance (µS/cm)	500	--	610	--	1,940	3
	Hardness (as $CaCO_3$)	140	--	250	--	730	3
	Calcium	35.0	--	58.0	--	110	3
	Magnesium	12.0	--	25.0	--	110	3
	Potassium	1.3	--	2.6	--	6.7	3
	Sodium-adsorption ratio (unitless)	0.20	--	2.9	--	3.2	3
	Sodium	5.5	--	87.0	--	180	3
	Alkalinity (as $CaCO_3$)	192	--	233	--	321	3
	Chloride	1.2	--	2.2	--	41.0	3
	Fluoride	0.30	--	0.30	--	1.0	3
	Silica	12.0	--	16.0	--	18.0	3
	Sulfate	66.0	--	87.0	--	700	3
	Total dissolved solids	287	--	383	--	1,360	3
Nugget aquifer	pH (standard units)	7.2	--	--	--	7.5	2
	Specific conductance (µS/cm)	560	--	--	--	2,070	2
	Hardness (as $CaCO_3$)	190	--	--	--	300	2
	Calcium	50.0	--	--	--	77.0	2
	Magnesium	16.0	--	--	--	25.0	2
	Potassium	1.0	--	--	--	6.4	2
	Sodium-adsorption ratio (unitless)	0.30	--	--	--	13.0	2
	Sodium	12.0	--	--	--	400	2
	Alkalinity (as $CaCO_3$)	219	--	--	--	295	2
	Chloride	4.0	--	--	--	42.0	2
	Fluoride	0.22	--	--	--	2.0	2
	Silica	13.0	--	--	--	--	1
	Sulfate	74.0	--	--	--	760	2
	Total dissolved solids	272	--	--	--	1,470	2

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater aquifer	pH (standard units)	7.1	7.2	7.4	7.6	7.9	11
	Specific conductance (µS/cm)	400	730	1,200	1,900	2,450	13
	Hardness (as $CaCO_3$)	190	330	425	580	1,100	10
	Calcium	48.0	79.0	109	158	312	10
	Magnesium	17.0	32.0	37.0	47.3	82.0	10
	Potassium	1.5	1.9	2.9	5.8	23.0	10
	Sodium-adsorption ratio (unitless)	0.20	0.30	0.65	1.1	2.8	10
	Sodium	6.0	12.3	34.5	42.5	130	10
	Alkalinity (as $CaCO_3$)	140	173	198	225	302	10
	Chloride	0.10	3.3	8.0	16.5	105	10
	Fluoride	0.10	0.30	0.35	0.56	1.8	10
	Silica	9.0	14.8	16.0	17.3	24.0	8
	Sulfate	12.0	88.3	310	483	981	10
	Total dissolved solids	211	392	669	1,020	1,640	10
	Nitrate+nitrite (as N)	--	0.038	0.11	0.50	--	7
	Boron	--	30.0	45.0	180	--	4
	Iron	--	10.0	53.0	960	--	7
	Manganese	--	1.2	15.0	20.0	--	5
	Selenium	--	0.85	1.5	5.0	--	4
Hydrogeologic units in Paleozoic lithostratigraphic units							
Phosphoria aquifer and confining unit	pH (standard units)	6.6	7.2	7.5	8.0	8.2	13
	Specific conductance (µS/cm)	365	475	995	1,700	4,230	14
	Hardness (as $CaCO_3$)	180	250	490	570	1,800	13
	Calcium	44.0	54.0	130	149	447	13
	Magnesium	16.0	29.0	36.0	50.0	171	13
	Potassium	1.1	2.2	7.4	8.6	19.0	13
	Sodium-adsorption ratio (unitless)	0.10	0.20	0.70	2.4	6.7	13
	Sodium	2.1	6.2	41.0	120	557	13
	Alkalinity (as $CaCO_3$)	148	160	237	309	602	13
	Chloride	0.10	4.7	28.0	43.0	219	13
	Fluoride	0.30	0.40	1.1	1.3	2.1	13
	Silica	7.2	10.0	12.0	14.0	21.0	13
	Sulfate	29.0	54.0	276	480	2,320	13
	Total dissolved solids	215	302	812	1,030	4,030	13
	Nitrate+nitrite (as N)	--	0.076	0.19	0.23	--	8
	Phosphorus, unfiltered (as P)	--	0.003	0.010	0.020	--	7

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Phosphoria aquifer and confining unit—Continued	Boron	--	20.0	90.0	160	--	6
	Iron	--	9.0	10.0	20.0	--	3
	Iron, unfiltered	--	90.0	290	440	--	3
Tensleep aquifer	pH (standard units)	6.8	7.4	7.6	7.9	8.5	13
	Specific conductance (µS/cm)	258	340	390	689	2,600	15
	Hardness (as $CaCO_3$)	142	160	192	223	559	12
	Calcium	31.0	36.0	42.0	51.0	158	15
	Magnesium	14.0	17.0	21.0	25.0	40.0	15
	Potassium	0.50	1.5	2.6	3.9	7.0	14
	Sodium-adsorption ratio (unitless)	0.10	0.10	0.10	0.10	0.30	6
	Sodium	1.6	2.9	4.0	7.5	93.0	15
	Alkalinity (as $CaCO_3$)	108	156	175	214	530	15
	Chloride	0.70	2.8	4.0	12.0	79.0	15
	Fluoride	0.10	0.20	0.30	0.60	1.2	11
	Silica	8.3	9.4	12.0	13.8	21.0	10
	Sulfate	2.9	12.1	22.5	43.0	482	15
	Total dissolved solids	146	192	208	244	1,060	15
	Nitrate+nitrite (as N)	--	0.090	0.20	0.20	--	5
	Boron	--	9.2	17.4	31.7	--	6
	Iron	--	18.9	23.8	29.9	--	5
	Gross alpha radioactivity (picocuries per liter)	--	2.9	11.6	31.5	--	4
	Gross beta radioactivity (picocuries per liter)	--	3.4	24.0	158	--	3
	Radium-226 (picocuries per liter)	--	0.65	1.3	3.6	--	5

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer	pH (standard units)	7.1	7.5	7.8	8.0	8.1	14
	Specific conductance (µS/cm)	349	378	405	430	1,190	14
	Hardness (as $CaCO_3$)	170	190	211	240	553	12
	Calcium	33.0	39.0	45.0	57.0	180	13
	Magnesium	12.0	20.0	22.0	26.0	33.7	13
	Potassium	0.50	1.0	2.0	4.0	7.5	13
	Sodium-adsorption ratio (unitless)	0.10	0.10	0.15	0.28	1.5	8
	Sodium	1.6	2.5	4.3	7.5	79.0	13
	Alkalinity (as $CaCO_3$)	104	172	192	201	502	13
	Chloride	0.90	2.1	4.3	6.0	29.8	13
	Fluoride	0.10	0.20	0.20	0.50	1.1	13
	Silica	7.5	8.6	10.3	20.0	24.0	12
	Sulfate	3.3	9.3	17.0	27.0	560	13
	Total dissolved solids	181	209	216	245	920	13
	Ammonia (as N)	--	0.020	0.020	0.030	--	5
	Nitrate+nitrite (as N)	--	0.080	0.20	0.92	--	11
	Phosphorus, unfiltered (as P)	--	0.006	0.009	0.020	--	8
	Boron	--	14.4	20.0	27.8	--	7
	Iron	--	3.0	60.0	140	--	7
	Manganese	--	0.85	20.0	80.0	--	7
	Gross alpha radioactivity (picocuries per liter)	--	1.2	2.7	6.8	--	6
	Gross beta radioactivity (picocuries per liter)	--	2.0	4.0	6.3	--	5
	Radium-226 (picocuries per liter)	--	0.92	1.2	2.7	--	4
	Uranium, natural	--	1.3	2.1	2.8	--	4

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bighorn aquifer	pH (standard units)	7.7	--	7.8	--	8.0	3
	Specific conductance (µS/cm)	180	--	330	--	480	3
	Hardness (as $CaCO_3$)	91.0	--	180	--	220	3
	Calcium	20.0	--	23.0	--	35.0	3
	Magnesium	10.0	--	30.0	--	32.0	3
	Potassium	0.90	--	0.90	--	1.4	3
	Sodium-adsorption ratio (unitless)	0.10	--	0.10	--	0.10	3
	Sodium	1.8	--	1.9	--	2.0	3
	Alkalinity (as $CaCO_3$)	93.0	--	177	--	216	3
	Chloride	0.50	--	1.2	--	1.3	3
	Fluoride	0.10	--	0.10	--	0.20	3
	Silica	7.2	--	8.0	--	8.6	3
	Sulfate	3.6	--	5.0	--	10.0	3
	Total dissolved solids	102	--	178	--	222	3
Gallatin confining unit	pH (standard units)	7.8	--	--	--	--	1
	Specific conductance (µS/cm)	520	--	--	--	--	1
	Hardness (as $CaCO_3$)	270	--	--	--	--	1
	Calcium	48.0	--	--	--	--	1
	Magnesium	36.0	--	--	--	--	1
	Potassium	2.9	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.20	--	--	--	--	1
	Sodium	8.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	236	--	--	--	--	1
	Chloride	1.7	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	9.7	--	--	--	--	1
	Sulfate	46.0	--	--	--	--	1
	Total dissolved solids	296	--	--	--	--	1

Appendix E1. Summary statistics for environmental water samples, Wind River Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Flathead aquifer	pH (standard units)	6.7	--	--	--	7.4	2
	Specific conductance (µS/cm)	56.0	--	--	--	410	2
	Hardness (as $CaCO_3$)	27.0	--	--	--	210	2
	Calcium	9.0	--	--	--	49.0	2
	Magnesium	1.1	--	--	--	21.0	2
	Potassium	0.50	--	--	--	2.5	2
	Sodium-adsorption ratio (unitless)	0.10	--	--	--	0.10	2
	Sodium	1.0	--	--	--	3.2	2
	Alkalinity (as $CaCO_3$)	27.0	--	--	--	201	2
	Chloride	0.50	--	--	--	1.1	2
	Fluoride	0.10	--	--	--	0.20	2
	Silica	6.0	--	--	--	8.9	2
	Sulfate	2.0	--	--	--	20.0	2
	Total dissolved solids	37.0	--	--	--	228	2
Precambrian lithostratigraphic units							
Precambrian basal confining unit	pH (standard units)	7.2	--	--	--	7.4	2
	Specific conductance (µS/cm)	184	--	--	--	342	2
	Hardness (as $CaCO_3$)	82.0	--	--	--	180	2
	Calcium	26.0	--	--	--	45.0	2
	Magnesium	4.2	--	--	--	16.0	2
	Potassium	0.60	--	--	--	0.70	2
	Sodium-adsorption ratio (unitless)	0.10	--	--	--	0.20	2
	Sodium	2.3	--	--	--	3.4	2
	Alkalinity (as $CaCO_3$)	83.0	--	--	--	182	2
	Chloride	0.50	--	--	--	0.60	2
	Fluoride	0.10	--	--	--	0.10	2
	Silica	10.0	--	--	--	16.0	2
	Sulfate	3.0	--	--	--	4.0	2
	Total dissolved solids	108	--	--	--	187	2

Appendix E2

Summary statistics for environmental water samples, Bighorn Basin, Wyoming

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Cenozoic lithostratigraphic units							
Quaternary alluvial aquifers	pH (standard units)	6.8	7.2	7.5	7.8	9.1	80
	Specific conductance (µS/cm)	98.0	921	1,580	2,320	7,530	81
	Hardness (as $CaCO_3$)	27.0	250	440	720	1,700	75
	Calcium	7.7	68.2	100	189	421	80
	Magnesium	1.8	22.5	36.0	62.8	488	80
	Potassium	0.50	2.3	3.0	4.4	62.0	77
	Sodium-adsorption ratio (unitless)	0.10	1.1	2.2	5.5	44.0	76
	Sodium	2.3	46.7	130	293	1,750	80
	Alkalinity (as $CaCO_3$)	46.0	230	303	382	857	80
	Bromide	0.01	0.03	0.06	0.08	0.10	8
	Chloride	0.10	3.6	9.5	24.0	359	87
	Fluoride	0.10	0.39	0.50	0.80	1.5	77
	Silica	2.8	13.0	19.0	25.0	40.0	73
	Sulfate	3.7	143	472	810	5,920	81
	Total dissolved solids	67.0	546	1,080	1,630	9,160	81
	Ammonia (as N)	--	0.006	0.026	0.090	--	29
	Nitrate+nitrite (as N)	--	0.14	1.7	6.5	--	55
	Nitrate (as N)	--	0.14	0.84	3.1	--	43
	Nitrite (as N)	--	0.002	0.006	0.020	--	28
	Orthophosphate (as P)	--	0.010	0.020	0.030	--	28
	Phosphorus (as P)	--	0.004	0.006	0.018	--	6
	Phosphorus, unfiltered (as P)	--	0.007	0.017	0.030	--	50
	Arsenic	--	0.82	1.3	2.1	--	11
	Barium	--	20.4	32.0	50.1	--	9
	Boron	--	55.0	145	240	--	28
	Cobalt	--	0.76	1.0	1.1	--	6
	Copper	--	1.2	2.0	3.1	--	7
	Iron	--	9.8	30.7	142	--	9
	Iron, unfiltered	--	60.0	110	200	--	16
	Manganese	--	25.0	392	723	--	9
	Molybdenum	--	1.5	2.2	3.3	--	7
	Nickel	--	2.4	4.1	7.0	--	7
	Selenium	--	1.1	2.1	3.8	--	19
	Zinc	--	0.96	1.5	2.3	--	7
	Gross alpha radioactivity (picocuries per liter)	--	5.9	10.5	19.3	--	8
	Gross beta radioactivity (picocuries per liter)	--	4.2	9.0	16.2	--	8

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers—Continued	Radon-222, unfiltered (picocuries per liter)	--	520	850	1,110	--	9
	Tritium, unfiltered (picocuries per liter)	--	52.0	65.8	111	--	8
	Uranium, natural	--	3.6	6.2	7.0	--	8
Quaternary terrace-deposit aquifers	pH (standard units)	6.9	7.3	7.5	7.7	8.4	76
	Specific conductance (µS/cm)	278	800	1,190	1,700	5,830	90
	Hardness (as $CaCO_3$)	53.0	270	370	600	3,700	61
	Calcium	0.80	58.8	95.5	130	410	64
	Magnesium	3.4	22.7	31.0	54.3	676	64
	Potassium	0.90	2.6	3.4	5.1	22.0	63
	Sodium-adsorption ratio (unitless)	0.60	1.9	2.8	4.2	26.0	60
	Sodium	29.0	81.7	125	229	775	64
	Alkalinity (as $CaCO_3$)	82.0	247	294	336	500	64
	Bromide	0.01	0.03	0.04	0.05	0.10	6
	Chloride	1.2	4.7	7.8	18.5	192	63
	Fluoride	0.20	0.60	0.80	1.4	4.2	63
	Silica	7.0	22.0	25.8	30.0	52.0	60
	Sulfate	44.0	180	351	699	4,350	64
	Total dissolved solids	265	593	879	1,400	6,360	64
	Ammonia (as N)	--	0.007	0.015	0.032	--	38
	Nitrate+nitrite (as N)	--	1.3	3.6	6.4	--	56
	Nitrate (as N)	--	0.89	2.8	4.7	--	32
	Nitrite (as N)	--	0.002	0.004	0.008	--	38
	Orthophosphate (as P)	--	0.010	0.020	0.030	--	36
	Phosphorus (as P)	--	0.013	0.031	0.042	--	6
	Phosphorus, unfiltered (as P)	--	0.010	0.018	0.030	--	20
	Aluminum	--	0.66	1.1	1.7	--	8
	Arsenic	--	1.7	2.4	3.5	--	12
	Barium	--	15.7	24.6	38.7	--	12
	Boron	--	120	190	290	--	45
	Chromium	--	0.52	0.62	0.76	--	12
	Copper	--	3.4	4.7	6.6	--	9
	Iron, unfiltered	--	50.0	95.0	210	--	28
	Manganese	--	0.67	3.1	20.0	--	10
	Molybdenum	--	1.7	3.0	6.0	--	7
	Nickel	--	1.7	2.3	3.0	--	9
	Selenium	--	2.2	3.4	5.3	--	27

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers—Continued	Zinc	--	0.98	2.6	13.8	--	9
	Gross alpha radioactivity (picocuries per liter)	--	1.3	2.8	7.0	--	12
	Gross beta radioactivity (picocuries per liter)	--	0.61	1.7	5.0	--	8
	Radon-222, unfiltered (picocuries per liter)	--	390	425	680	--	10
	Tritium, unfiltered (picocuries per liter)	--	42.6	45.2	49.0	--	6
	Uranium, natural	--	3.8	4.8	16.4	--	10
Willwood aquifer	pH (standard units)	6.7	7.7	8.1	8.4	9.3	83
	Specific conductance (µS/cm)	607	1,300	1,950	2,680	10,200	83
	Hardness (as $CaCO_3$)	2.0	27.5	125	323	1,900	80
	Calcium	0.20	7.1	34.5	80.7	407	84
	Magnesium	0.10	2.4	9.2	24.2	214	84
	Potassium	0.20	2.2	3.6	5.3	54.0	84
	Sodium-adsorption ratio (unitless)	1.2	10.5	23.0	30.5	110	79
	Sodium	58.0	258	369	561	2,200	84
	Alkalinity (as $CaCO_3$)	122	228	309	392	893	84
	Bromide	0.06	0.11	0.14	0.20	0.64	13
	Chloride	3.2	22.0	59.5	103	354	84
	Fluoride	0.20	0.91	1.5	2.4	6.4	82
	Silica	4.2	6.6	7.4	9.1	29.0	74
	Sulfate	0.60	174	594	1,050	6,000	84
	Total dissolved solids	352	812	1,350	1,930	9,000	84
	Ammonia (as N)	--	0.042	0.20	0.78	--	24
	Nitrate+nitrite (as N)	--	0.077	0.67	3.2	--	44
	Nitrate (as N)	--	0.050	0.26	0.86	--	18
	Nitrite (as N)	--	0.001	0.003	0.007	--	24
	Orthophosphate (as P)	--	0.010	0.020	0.020	--	19
	Phosphorus (as P)	--	0.006	0.010	0.015	--	13
	Phosphorus, unfiltered (as P)	--	0.006	0.010	0.019	--	24
	Aluminum	--	0.26	1.7	11.0	--	20
	Arsenic	--	0.61	1.2	2.2	--	21
	Barium	--	7.9	13.5	23.0	--	22
	Boron	--	130	160	220	--	55
	Cadmium	--	0.006	0.028	0.13	--	17
	Chromium	--	0.40	0.51	0.64	--	22

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Willwood aquifer—Continued	Cobalt	--	0.013	0.048	0.18	--	18
	Copper	--	1.0	2.8	7.6	--	18
	Iron	--	1.5	5.7	22.4	--	20
	Iron, unfiltered	--	110	125	450	--	18
	Lithium	--	28.0	46.7	77.7	--	18
	Manganese	--	1.0	5.3	62.1	--	19
	Molybdenum	--	3.1	6.1	14.7	--	13
	Nickel	--	0.11	0.39	1.4	--	18
	Selenium	--	0.47	2.4	10.0	--	33
	Strontium	--	65.6	225	625	--	13
	Vanadium	--	0.12	0.34	0.97	--	18
	Zinc	--	2.3	7.6	23.6	--	17
	Gross alpha radioactivity (picocuries per liter)	--	0.54	1.7	7.0	--	20
	Gross beta radioactivity (picocuries per liter)	--	2.7	4.9	8.0	--	17
	Radium-226 (picocuries per liter)	--	0.043	0.13	1.0	--	10
	Radium-228 (picocuries per liter)	--	0.93	1.0	1.1	--	7
	Radon-222, unfiltered (picocuries per liter)	--	600	775	1,430	--	14
	Uranium, natural	--	0.31	1.3	11.7	--	21
Fort Union aquifer	pH (standard units)	7.1	7.4	7.8	8.2	8.8	32
	Specific conductance (µS/cm)	580	1,380	2,350	3,340	6,390	31
	Hardness (as $CaCO_3$)	12.0	105	220	635	1,300	31
	Calcium	2.9	28.1	76.5	143	270	32
	Magnesium	0.90	5.3	15.0	59.5	220	32
	Potassium	1.6	3.1	4.7	6.6	14.0	32
	Sodium-adsorption ratio (unitless)	0.20	7.0	11.0	31.0	48.0	31
	Sodium	11.4	254	393	647	1,560	32
	Alkalinity (as $CaCO_3$)	194	296	404	464	787	32
	Bromide	0.05	0.09	0.11	0.17	0.20	5
	Chloride	4.0	15.4	43.3	72.0	410	32
	Fluoride	0.30	0.69	1.1	2.1	4.1	32
	Silica	5.5	7.3	8.8	11.5	18.0	30
	Sulfate	4.2	403	714	1,500	2,900	32
	Total dissolved solids	372	870	1,550	2,670	4,920	32
	Ammonia (as N)	--	0.33	0.77	2.7	--	6

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fort Union aquifer—Continued	Nitrate+nitrite (as N)	--	0.031	0.12	1.9	--	18
	Nitrate (as N)	--	0.080	0.37	0.79	--	5
	Nitrite (as N)	--	0.003	0.005	0.010	--	6
	Orthophosphate (as P)	--	0.017	0.030	0.030	--	5
	Phosphorus (as P)	--	0.006	0.016	0.034	--	5
	Arsenic	--	0.49	0.78	1.2	--	10
	Barium	--	7.1	13.7	26.2	--	10
	Boron	--	140	180	264	--	21
	Chromium	--	0.53	0.88	1.4	--	10
	Cobalt	--	0.16	0.20	0.25	--	6
	Copper	--	1.9	3.0	4.6	--	9
	Iron	--	17.0	59.0	450	--	10
	Iron, unfiltered	--	50.0	110	260	--	9
	Lithium	--	11.8	18.6	28.6	--	6
	Manganese	--	7.8	20.0	109	--	10
	Molybdenum	--	0.80	1.4	2.4	--	5
	Selenium	--	0.66	1.9	5.6	--	15
	Strontium	--	369	414	557	--	5
	Zinc	--	4.3	13.2	140	--	9
	Gross alpha radioactivity (picocuries per liter)	--	0.91	3.3	5.6	--	6
	Gross beta radioactivity (picocuries per liter)	--	7.0	8.8	10.3	--	6
	Radium-228 (picocuries per liter)	--	1.0	1.0	1.7	--	3
	Radon-222, unfiltered (picocuries per liter)	--	390	450	460	--	5
	Uranium, natural	--	0.56	1.2	3.0	--	7

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Mesozoic lithostratigraphic units							
Lance aquifer	pH (standard units)	7.5	7.8	8.6	8.6	9.0	8
	Specific conductance (µS/cm)	948	1,150	1,410	1,590	1,960	7
	Hardness (as $CaCO_3$)	7.0	13.0	20.0	305	450	7
	Calcium	2.3	3.3	5.6	49.3	97.0	8
	Magnesium	0.30	0.70	1.1	23.8	58.0	8
	Potassium	0.20	1.5	2.0	3.2	5.9	7
	Sodium-adsorption ratio (unitless)	0.80	2.9	15.0	35.0	45.0	5
	Sodium	34.0	242	287	364	420	8
	Alkalinity (as $CaCO_3$)	287	377	450	513	777	8
	Chloride	10.0	36.3	69.5	83.0	110	8
	Fluoride	0.30	0.75	2.9	4.1	4.4	7
	Silica	2.3	8.6	9.5	10.7	11.0	6
	Sulfate	2.8	24.9	185	325	460	8
	Total dissolved solids	591	670	902	964	1,260	8
	Boron	--	130	160	280	--	5
Meeteetse aquifer and confining unit	pH (standard units)	7.3	7.7	8.1	8.4	9.0	5
	Specific conductance (µS/cm)	1,400	1,510	1,690	1,840	2,000	5
	Hardness (as $CaCO_3$)	64.0	380	430	550	580	5
	Calcium	35.0	39.0	75.0	80.0	100	5
	Magnesium	11.0	70.0	81.0	81.0	86.0	5
	Potassium	4.0	5.1	7.0	11.0	11.0	5
	Sodium-adsorption ratio (unitless)	1.8	3.7	4.9	7.0	9.4	5
	Sodium	100	200	232	310	330	5
	Alkalinity (as $CaCO_3$)	323	444	550	564	809	5
	Chloride	7.2	13.0	16.0	25.0	43.0	5
	Fluoride	0.10	0.10	0.50	0.90	1.4	5
	Silica	6.7	9.7	11.0	14.0	21.0	5
	Sulfate	207	250	470	530	561	5
	Total dissolved solids	936	968	1,200	1,320	1,400	5
	Barium	--	18.0	19.0	19.0	--	3
	Boron	--	100	110	130	--	5
	Chromium	--	1.0	2.0	2.0	--	3
	Copper	--	1.0	4.0	10.0	--	3
	Iron	--	13.0	41.0	610	--	3
	Manganese	--	16.0	45.0	130	--	3
	Zinc	--	34.0	36.0	99.0	--	3

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mesaverde aquifer	pH (standard units)	7.0	7.4	7.6	7.9	8.5	24
	Specific conductance (µS/cm)	200	1,900	2,410	3,010	6,800	24
	Hardness (as $CaCO_3$)	9.0	300	630	1,400	2,200	25
	Calcium	2.0	46.0	118	234	450	26
	Magnesium	1.0	44.0	58.0	157	360	26
	Potassium	2.4	3.5	8.5	12.5	21.0	26
	Sodium-adsorption ratio (unitless)	0.40	2.1	3.5	9.0	86.0	24
	Sodium	36.0	98.3	267	401	970	26
	Alkalinity (as $CaCO_3$)	186	320	454	628	1,100	26
	Chloride	3.0	11.3	20.0	30.8	420	26
	Fluoride	0.10	0.40	0.70	0.90	3.4	25
	Silica	5.9	7.5	9.8	12.0	22.0	24
	Sulfate	104	353	820	1,380	3,200	26
	Total dissolved solids	395	1,210	1,770	2,400	5,510	26
	Nitrate+nitrite (as N)	--	0.029	0.30	0.73	--	15
	Nitrate (as N)	--	0.014	0.090	0.36	--	4
	Phosphorus, unfiltered (as P)	--	0.005	0.007	0.010	--	16
	Boron	--	160	275	370	--	18
	Copper	--	1.0	1.0	5.5	--	4
	Iron	--	19.0	70.0	1,100	--	7
	Iron, unfiltered	--	40.0	1,200	6,700	--	7
	Manganese	--	13.0	39.0	120	--	7
	Mercury	--	0.14	0.17	0.22	--	5
	Selenium	--	1.2	2.1	3.8	--	11
	Zinc	--	8.0	15.0	34.0	--	4
Cody confining unit	pH (standard units)	7.4	7.5	7.7	7.9	9.1	9
	Specific conductance (µS/cm)	1,000	1,920	4,010	5,200	8,800	9
	Hardness (as $CaCO_3$)	4.0	48.5	565	1,430	2,000	10
	Calcium	1.3	15.0	113	288	370	10
	Magnesium	0.20	2.9	63.5	165	280	10
	Potassium	1.0	1.9	2.9	6.5	10.0	10
	Sodium-adsorption ratio (unitless)	1.7	8.2	9.6	42.3	120	10
	Sodium	110	385	579	885	2,000	10
	Alkalinity (as $CaCO_3$)	197	341	439	570	2,070	10
	Bromide	0.04	--	--	--	--	1
	Chloride	3.8	17.5	45.0	183	640	10

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cody confining unit—Continued	Fluoride	0.10	0.43	0.60	1.6	3.4	10
	Silica	7.9	8.6	11.0	15.5	22.0	10
	Sulfate	5.6	463	895	2,340	5,200	10
	Total dissolved solids	660	1,370	2,350	4,080	8,290	10
	Nitrate+nitrite (as N)	--	0.005	0.055	0.74	--	7
	Phosphorus, unfiltered (as P)	--	0.010	0.020	0.040	--	7
	Boron	--	420	970	1,300	--	7
	Selenium	--	0.35	1.2	8.0	--	6
Frontier aquifer	pH (standard units)	6.8	7.5	8.6	9.1	9.2	12
	Specific conductance (µS/cm)	1,170	1,580	2,190	2,790	6,680	12
	Hardness (as $CaCO_3$)	2.0	4.0	134	670	1,000	12
	Calcium	0.83	1.3	37.7	158	200	12
	Magnesium	0.06	0.19	10.4	48.8	134	12
	Potassium	0.60	0.80	2.0	5.6	11.0	12
	Sodium-adsorption ratio (unitless)	1.1	6.2	48.0	76.8	130	12
	Sodium	67.0	285	365	531	1,670	12
	Alkalinity (as $CaCO_3$)	124	249	341	548	694	12
	Bromide	0.03	--	--	--	--	1
	Chloride	2.9	5.9	12.0	18.3	35.0	12
	Fluoride	0.30	0.68	1.3	1.8	2.9	12
	Silica	8.3	9.8	14.0	14.8	31.0	12
	Sulfate	170	310	796	1,240	3,040	12
	Total dissolved solids	758	1,010	1,530	2,110	5,210	12
	Nitrate+nitrite (as N)	--	0.038	0.10	0.43	--	8
	Phosphorus, unfiltered (as P)	--	0.020	0.080	0.18	--	7
	Boron	--	140	215	580	--	10
	Iron	--	33.0	52.0	100	--	5
	Iron, unfiltered	--	30.0	170	250	--	3
	Manganese	--	5.0	6.0	9.0	--	5

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mowry confining unit	pH (standard units)	7.2	7.5	7.7	8.0	8.4	4
	Specific conductance (µS/cm)	565	815	1,100	1,750	16,800	5
	Hardness (as $CaCO_3$)	28.0	79.0	160	380	3,000	7
	Calcium	8.8	21.0	39.0	101	370	7
	Magnesium	1.4	6.5	16.0	31.5	517	7
	Potassium	0.60	2.6	3.3	4.6	14.0	7
	Sodium-adsorption ratio (unitless)	2.6	4.1	4.8	51.5	83.0	7
	Sodium	89.0	113	220	1,200	4,580	7
	Alkalinity (as $CaCO_3$)	167	237	301	416	525	7
	Chloride	2.3	4.8	5.1	47.5	146	7
	Fluoride	0.50	0.70	0.70	3.0	5.0	7
	Silica	6.5	9.3	11.0	15.0	24.0	7
	Sulfate	120	269	590	2,100	12,100	7
	Total dissolved solids	362	648	1,150	3,670	19,200	7
	Nitrate (as N)	--	0.50	1.6	2.5	--	3
	Phosphorus, unfiltered (as P)	--	0.020	0.050	0.070	--	5
	Boron	--	140	180	370	--	5
	Iron	--	23.0	110	310	--	3
	Manganese	--	4.0	5.0	96.0	--	3
Muddy Sandstone aquifer	pH (standard units)	8.0	8.6	8.9	9.0	9.1	5
	Specific conductance (µS/cm)	1,100	1,610	1,720	1,750	2,450	5
	Hardness (as $CaCO_3$)	2.0	3.5	4.0	4.3	5.0	4
	Calcium	0.60	0.60	0.90	1.2	1.2	4
	Magnesium	0.10	0.18	0.35	0.55	0.70	4
	Potassium	0.40	0.80	0.90	1.7	1.8	5
	Sodium-adsorption ratio (unitless)	78.0	82.5	88.5	102	130	4
	Sodium	248	378	428	448	660	5
	Alkalinity (as $CaCO_3$)	228	299	432	611	1,150	5
	Chloride	1.3	5.2	9.2	14.0	200	5
	Fluoride	0.40	0.60	0.80	2.3	4.7	5
	Silica	8.5	11.0	12.0	25.0	26.0	5
	Sulfate	3.6	180	253	430	431	5
	Total dissolved solids	688	1,040	1,100	1,140	1,570	5
	Boron	--	120	195	615	--	4
	Iron, unfiltered	--	50.0	80.0	270	--	5

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Thermopolis confining unit	pH (standard units)	4.3	6.6	7.4	7.7	8.4	4
	Specific conductance (µS/cm)	371	965	1,010	2,180	40,000	5
	Hardness (as $CaCO_3$)	46.0	190	230	250	2,500	5
	Calcium	12.0	40.0	57.0	62.0	290	5
	Magnesium	3.9	21.0	22.0	22.0	430	5
	Potassium	0.50	2.0	3.1	4.4	27.0	5
	Sodium-adsorption ratio (unitless)	0.20	3.3	3.5	32.0	61.0	5
	Sodium	5.5	120	120	507	7,000	5
	Alkalinity (as $CaCO_3$)	1.0	144	265	280	323	5
	Chloride	1.2	3.6	5.6	5.7	180	5
	Fluoride	0.10	0.40	0.90	1.9	3.0	5
	Silica	9.3	13.0	14.0	20.0	56.0	5
	Sulfate	50.0	220	240	785	17,000	5
	Total dissolved solids	218	599	638	1,500	25,100	5
	Phosphorus, unfiltered (as P)	--	0.020	0.090	0.18	--	3
	Boron	--	50.0	160	460	--	4
	Iron	--	4.0	120	520	--	3
	Iron, unfiltered	--	30.0	240	4,800	--	3
	Manganese	--	4.0	910	60,000	--	3
Cloverly aquifer	pH (standard units)	7.0	7.6	7.9	8.1	9.0	6
	Specific conductance (µS/cm)	1,300	2,270	2,660	3,260	3,650	8
	Hardness (as $CaCO_3$)	10.0	58.3	530	793	1,700	10
	Calcium	3.0	12.5	115	200	485	10
	Magnesium	0.70	6.8	58.5	74.5	126	10
	Potassium	1.3	2.7	4.7	5.5	6.1	10
	Sodium-adsorption ratio (unitless)	1.5	6.6	10.8	35.3	84.0	10
	Sodium	140	306	535	658	816	10
	Alkalinity (as $CaCO_3$)	35.0	155	256	279	607	10
	Chloride	3.8	8.9	14.5	19.3	38.0	10
	Fluoride	0.40	0.73	1.1	1.6	3.3	10
	Silica	3.4	8.4	11.0	11.8	20.0	10
	Sulfate	330	991	1,320	1,800	2,000	10
	Total dissolved solids	814	1,670	2,350	2,830	3,080	10
	Boron	--	460	500	1,200	--	7
	Iron, unfiltered	--	60.0	70.0	590	--	5

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

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Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit and aquifer	pH (standard units)	8.4	--	--	--	--	1
	Specific conductance (µS/cm)	947	--	--	--	5,190	2
	Hardness (as $CaCO_3$)	480	--	--	--	1,700	2
	Calcium	86.0	--	--	--	428	2
	Magnesium	65.0	--	--	--	149	2
	Potassium	9.0	--	--	--	14.0	2
	Sodium-adsorption ratio (unitless)	0.60	--	--	--	8.4	2
	Sodium	29.0	--	--	--	794	2
	Alkalinity (as $CaCO_3$)	274	--	--	--	352	2
	Chloride	2.7	--	--	--	14.0	2
	Fluoride	1.2	--	--	--	1.4	2
	Silica	20.0	--	--	--	74.0	2
	Sulfate	186	--	--	--	3,000	2
	Total dissolved solids	604	--	--	--	4,780	2
Sundance confining unit and aquifer	pH (standard units)	7.3	--	--	--	--	1
	Specific conductance (µS/cm)	1,020	--	--	--	--	1
	Hardness (as $CaCO_3$)	550	--	--	--	--	1
	Calcium	110	--	--	--	--	1
	Magnesium	66.0	--	--	--	--	1
	Potassium	2.5	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	0.80	--	--	--	--	1
	Sodium	43.0	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	323	--	--	--	--	1
	Chloride	2.7	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	13.0	--	--	--	--	1
	Sulfate	270	--	--	--	--	1
	Total dissolved solids	708	--	--	--	--	1

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Gypsum Spring confining unit and aquifer	pH (standard units)	7.3	--	8.0	--	8.2	3
	Specific conductance (µS/cm)	531	1,630	2,100	2,380	2,900	4
	Hardness (as $CaCO_3$)	200	755	1,170	1,500	1,800	4
	Calcium	37.0	212	337	438	540	4
	Magnesium	25.0	54.3	85.0	107	110	4
	Potassium	1.7	3.5	4.5	5.0	5.4	4
	Sodium-adsorption ratio (unitless)	0.40	0.85	1.1	1.3	1.4	4
	Sodium	36.0	43.5	65.0	88.0	100	4
	Alkalinity (as CaCO3)	116	118	123	141	183	4
	Chloride	2.0	2.3	2.5	2.7	3.1	4
	Fluoride	0.60	0.68	0.75	0.90	1.2	4
	Silica	16.0	18.3	20.0	23.3	30.0	4
	Sulfate	104	754	1,150	1,440	1,800	4
	Total dissolved solids	342	1,200	1,830	2,280	2,650	4
Chugwater aquifer	pH (standard units)	6.4	7.2	7.4	7.6	7.8	12
	Specific conductance (µS/cm)	420	1,670	2,360	2,730	4,200	12
	Hardness (as $CaCO_3$)	200	833	1,400	1,530	1,900	12
	Calcium	41.0	230	380	500	570	13
	Magnesium	24.0	44.0	71.0	92.0	130	13
	Potassium	1.0	1.3	3.3	5.2	7.0	13
	Sodium-adsorption ratio (unitless)	0.10	0.38	0.40	1.3	2.0	12
	Sodium	11.0	18.0	24.0	110	170	13
	Alkalinity (as $CaCO_3$)	131	136	181	210	295	13
	Bromide	0.05	--	--	--	--	1
	Chloride	0.90	2.5	4.5	6.5	37.0	13
	Fluoride	0.30	0.40	0.60	0.80	1.0	13
	Silica	11.0	11.0	16.5	20.3	35.0	12
	Sulfate	24.0	870	1,300	1,500	1,900	13
	Total dissolved solids	251	1,450	1,960	2,320	2,840	13
	Nitrate+nitrite (as N)	--	0.74	1.3	3.0	--	12
	Phosphorus, unfiltered (as P)	--	0.007	0.009	0.010	--	11
	Boron	--	90.0	120	540	--	10
	Iron	--	7.0	11.5	60.0	--	8
	Manganese	--	2.0	5.5	20.0	--	8
	Selenium	--	2.0	5.0	29.0	--	3

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Goose Egg aquifer and confining unit	pH (standard units)	7.6	7.7	7.8	7.8	8.0	9
	Specific conductance (µS/cm)	381	515	696	1,150	2,700	9
	Hardness (as $CaCO_3$)	200	248	350	640	1,600	12
	Calcium	43.0	58.3	78.0	190	589	12
	Magnesium	18.0	25.3	34.0	40.5	77.0	12
	Potassium	0.90	1.4	1.9	3.9	5.6	12
	Sodium-adsorption ratio (unitless)	0.10	0.10	0.10	0.25	1.1	11
	Sodium	1.6	3.1	4.6	9.6	100	12
	Alkalinity (as $CaCO_3$)	137	179	180	189	312	12
	Chloride	0.10	1.6	1.8	3.0	48.0	12
	Fluoride	0.20	0.30	0.40	0.73	3.4	12
	Silica	7.4	9.4	11.0	18.0	26.0	12
	Sulfate	9.1	30.3	144	459	1,560	12
	Total dissolved solids	205	288	397	864	2,690	12
	Nitrate (as N)	--	0.12	0.22	0.75	--	8
	Phosphorus, unfiltered (as P)	--	0.004	0.010	0.010	--	9
Hydrogeologic units in Paleozoic lithostratigraphic units							
Phosphoria aquifer and confining unit	pH (standard units)	5.8	--	6.7	--	7.3	3
	Specific conductance (µS/cm)	1,080	--	3,270	--	4,730	3
	Hardness (as $CaCO_3$)	580	1,200	2,000	2,000	5,000	5
	Calcium	130	350	532	566	962	5
	Magnesium	62.0	79.0	154	155	639	5
	Potassium	3.7	--	44.0	--	160	3
	Sodium-adsorption ratio (unitless)	0.30	2.6	3.7	28.1	100	4
	Sodium	16.0	140	260	420	16,500	5
	Alkalinity (as $CaCO_3$)	178	552	1,070	1,090	1,200	5
	Bromide	1.1	--	--	--	--	1
	Chloride	4.4	86.0	330	368	21,900	5
	Fluoride	1.5	--	3.1	--	4.1	3
	Silica	9.7	27.2	36.0	40.8	46.0	4
	Sulfate	450	795	941	1,070	1,350	4
	Total dissolved solids	787	2,340	2,840	3,730	49,400	5
	Boron	--	60.0	1,100	100,000	--	3

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Tensleep aquifer	pH (standard units)	5.8	7.5	7.7	7.9	8.5	36
	Specific conductance (µS/cm)	307	396	460	835	3,570	35
	Hardness (as $CaCO_3$)	150	200	240	340	2,600	37
	Calcium	30.0	44.5	52.0	92.5	601	43
	Magnesium	15.0	20.5	27.0	38.0	279	43
	Potassium	0.50	1.3	2.1	4.5	50.0	43
	Sodium-adsorption ratio (unitless)	0.10	0.10	0.10	0.30	3.5	33
	Sodium	1.0	2.2	5.4	13.0	360	43
	Alkalinity (as $CaCO_3$)	87.0	167	205	233	622	43
	Bromide	1.1	--	--	--	--	1
	Chloride	0.10	1.8	3.0	7.8	340	43
	Fluoride	0.10	0.20	0.48	1.1	9.4	38
	Silica	6.3	9.0	9.9	10.0	42.0	37
	Sulfate	1.0	13.5	35.0	203	2,340	43
	Total dissolved solids	156	219	259	545	3,750	44
	Nitrate+nitrite (as N)	--	0.12	0.96	2.0	--	8
	Nitrate (as N)	--	0.050	0.18	0.47	--	18
	Phosphorus, unfiltered (as P)	--	0.006	0.008	0.010	--	17
	Boron	--	20.0	40.0	210	--	19
	Iron, unfiltered	--	30.0	105	250	--	18
	Gross alpha radioactivity (picocuries per liter)	--	1.0	7.0	7.0	--	3
	Radium-226 (picocuries per liter)	--	2.4	2.6	3.2	--	3
	Uranium, natural	--	2.1	3.5	4.1	--	4

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer	pH (standard units)	6.2	7.6	7.7	7.9	8.1	38
	Specific conductance (µS/cm)	325	353	406	630	9,970	27
	Hardness (as $CaCO_3$)	130	190	220	237	2,190	27
	Calcium	20.0	40.0	46.5	54.3	651	42
	Magnesium	14.0	21.0	24.0	26.6	270	42
	Potassium	0.50	0.90	1.3	2.3	130	42
	Sodium-adsorption ratio (unitless)	0.05	0.10	0.10	0.10	22.0	17
	Sodium	1.2	1.8	2.7	5.7	2,300	42
	Alkalinity (as $CaCO_3$)	65.0	185	198	220	366	42
	Chloride	0.10	0.80	1.0	3.2	378	41
	Fluoride	0.15	0.20	0.32	0.74	5.4	40
	Silica	1.4	8.8	9.6	12.0	39.0	38
	Sulfate	2.5	8.1	18.3	86.3	6,900	42
	Total dissolved solids	173	203	232	355	9,980	42
	Nitrate+nitrite (as N)	--	0.26	0.40	0.48	--	16
	Nitrate (as N)	--	0.11	0.29	0.47	--	9
	Boron	--	9.2	32.2	113	--	11
	Iron	--	8.6	46.6	260	--	8
	Iron, unfiltered	--	24.8	50.0	340	--	4
	Lead	--	1.3	3.4	9.4	--	8
	Selenium	--	1.4	2.5	4.3	--	8
	Gross alpha radioactivity (picocuries per liter)	--	2.5	5.2	18.0	--	4
	Gross beta radioactivity (picocuries per liter)	--	1.0	2.0	5.4	--	5
	Radium-226 (picocuries per liter)	--	1.1	2.2	5.8	--	4
	Radium-226, radon method (picocuries per liter)	--	0.64	0.86	36.0	--	13
	Uranium, natural	--	2.0	3.0	4.0	--	5

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bighorn aquifer	pH (standard units)	6.2	6.8	7.4	7.7	9.0	5
	Specific conductance (µS/cm)	265	390	452	511	4,210	6
	Hardness (as $CaCO_3$)	140	203	216	236	2,000	6
	Calcium	35.0	38.5	47.5	49.8	614	6
	Magnesium	2.6	20.8	28.0	34.5	122	6
	Potassium	0.80	1.1	1.8	4.3	160	6
	Sodium-adsorption ratio (unitless)	0.10	--	0.10	--	2.7	3
	Sodium	0.40	1.6	2.5	3.7	284	6
	Alkalinity (as $CaCO_3$)	140	188	196	229	992	6
	Chloride	0.50	0.70	1.1	1.3	272	6
	Fluoride	0.10	0.20	0.20	0.40	3.4	5
	Silica	0.02	4.9	8.4	9.7	30.0	6
	Sulfate	0.40	6.3	9.5	16.5	1,360	6
	Total dissolved solids	136	203	230	257	3,410	6
	Nitrate+nitrite (as N)	--	0.38	0.52	0.56	--	4
	Boron	--	11.7	34.8	92.9	--	6
	Iron	--	10.0	28.5	87.5	--	4
Gros Ventre confining unit	pH (standard units)	7.4	--	--	--	--	1
	Specific conductance (µS/cm)	365	--	--	--	4,200	2
	Hardness (as $CaCO_3$)	190	--	--	--	1,100	2
	Calcium	56.0	--	--	--	429	2
	Magnesium	7.2	--	--	--	13.0	2
	Potassium	12.0	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	7.0	--	--	--	--	1
	Sodium	3.2	--	--	--	530	2
	Alkalinity (as $CaCO_3$)	30.0	--	--	--	189	2
	Chloride	3.8	--	--	--	839	2
	Fluoride	2.5	--	--	--	--	1
	Silica	3.6	--	--	--	19.0	2
	Sulfate	6.2	--	--	--	1,010	2
	Total dissolved solids	210	--	--	--	3,010	2

Appendix E2. Summary statistics for environmental water samples, Bighorn Basin, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Flathead aquifer	pH (standard units)	6.7	7.8	8.0	8.1	8.7	12
	Specific conductance (µS/cm)	70.0	217	295	360	690	12
	Hardness (as $CaCO_3$)	23.0	60.8	110	123	280	12
	Calcium	7.6	18.0	22.0	29.8	62.0	12
	Magnesium	0.90	3.9	9.2	15.3	31.0	12
	Potassium	0.50	1.0	4.0	6.0	15.0	12
	Sodium-adsorption ratio (unitless)	0.10	0.13	0.30	0.50	14.0	10
	Sodium	0.80	2.6	8.3	13.8	150	12
	Alkalinity (as $CaCO_3$)	24.0	96.0	131	144	250	12
	Chloride	0.10	0.83	1.8	2.2	20.0	12
	Fluoride	0.10	0.18	0.35	0.40	1.9	12
	Silica	4.4	9.9	11.0	12.5	15.0	11
	Sulfate	5.0	8.8	18.0	28.8	160	12
	Total dissolved solids	58.0	120	163	209	443	12
	Nitrate+nitrite (as N)	--	0.11	0.81	0.88	--	5
	Nitrate (as N)	--	0.045	0.090	0.16	--	4
	Boron	--	10.0	30.0	140	--	5
	Iron	--	14.0	17.0	27.0	--	5
	Manganese	--	0.40	1.0	2.0	--	5
Hydrogeologic units in Precambrian lithostratigraphic units							
Precambrian basal confining unit	pH (standard units)	7.4	--	7.8	--	8.8	3
	Specific conductance (µS/cm)	160	--	212	--	435	3
	Hardness (as $CaCO_3$)	50.0	--	65.0	--	270	3
	Calcium	17.0	--	17.0	--	69.0	3
	Magnesium	1.8	--	5.5	--	23.0	3
	Potassium	0.40	--	2.1	--	4.6	3
	Sodium-adsorption ratio (unitless)	0.10	--	0.10	--	0.50	3
	Sodium	1.9	--	4.5	--	8.8	3
	Alkalinity (as $CaCO_3$)	69.0	--	75.0	--	234	3
	Chloride	0.40	--	1.6	--	2.2	3
	Fluoride	0.10	--	0.20	--	0.20	3
	Silica	5.2	--	8.7	--	22.0	3
	Sulfate	2.6	--	5.2	--	34.0	3
	Total dissolved solids	75.0	--	111	--	284	3

Appendix E3

Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Cenozoic lithostratigraphic units							
Quaternary alluvial aquifers	pH (standard units)	4.4	6.1	6.7	7.4	9.2	38
	Specific conductance (µS/cm)	78.0	155	210	514	1,950	37
	Hardness (as $CaCO_3$)	8.0	14.3	30.5	50.8	260	38
	Calcium	2.8	5.1	7.9	16.0	71.0	38
	Magnesium	0.02	0.75	1.9	3.6	22.0	38
	Potassium	0.50	3.6	5.7	8.2	31.0	38
	Sodium-adsorption ratio (unitless)	0.20	1.8	4.0	7.3	46.0	19
	Sodium	2.8	13.4	31.0	84.0	377	38
	Alkalinity (as $CaCO_3$)	21.0	53.0	75.0	132	748	37
	Chloride	0.20	1.6	5.6	30.0	619	37
	Fluoride	0.10	0.55	2.7	6.6	9.9	31
	Silica	1.8	30.4	64.5	99.0	460	38
	Sulfate	1.0	4.2	9.1	16.8	48.0	38
	Total dissolved solids	57.0	128	182	376	1,550	38
	Ammonia (as N)	--	0.060	0.11	0.25	--	8
	Nitrate+nitrite (as N)	--	0.11	0.32	1.5	--	11
	Phosphorus, unfiltered (as P)	--	0.050	0.080	0.15	--	11
	Aluminum	--	0.65	90.0	115	--	12
	Arsenic	--	3.2	58.6	242	--	10
	Barium	--	6.0	15.0	24.0	--	12
	Boron	--	40.0	90.0	640	--	27
	Bromine	--	0.064	1.5	1.8	--	7
	Copper	--	1.1	2.0	4.0	--	5
	Iron	--	30.0	50.0	150	--	35
	Lead	--	<0.001	0.007	1.0	--	10
	Lithium	--	20.0	70.0	2,360	--	11
	Manganese	--	7.0	20.0	60.0	--	18
	Molybdenum	--	2.0	5.0	30.0	--	9
	Strontium	--	10.0	20.0	46.0	--	11
	Zinc	--	15.0	30.7	62.7	--	7
	Gross alpha radioactivity (picocuries per liter)	--	1.3	1.4	2.3	--	3
	Gross beta radioactivity (picocuries per liter)	--	5.5	5.7	8.0	--	3

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in Quaternary landslide deposits	pH (standard units)	7.9	--	--	--	--	1
	Specific conductance (µS/cm)	256	--	--	--	--	1
	Hardness (as $CaCO_3$)	130	--	--	--	--	1
	Calcium	39.0	--	--	--	--	1
	Magnesium	8.6	--	--	--	--	1
	Potassium	0.50	--	--	--	--	1
	Sodium	2.4	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	168	--	--	--	--	1
	Chloride	0.50	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	19.0	--	--	--	--	1
	Sulfate	5.0	--	--	--	--	1
	Total dissolved solids	158	--	--	--	--	1
Aquifers in Quaternary lacustrine deposits	pH (standard units)	5.9	6.6	6.9	7.2	8.3	38
	Specific conductance (µS/cm)	26.0	85.5	114	165	442	38
	Hardness (as $CaCO_3$)	10.0	27.0	42.0	62.8	180	38
	Calcium	3.2	6.9	9.8	14.8	43.0	38
	Magnesium	0.50	2.5	4.2	6.4	19.0	38
	Potassium	1.6	2.4	2.9	3.8	13.0	38
	Sodium-adsorption ratio (unitless)	0.10	0.20	0.30	0.30	0.80	30
	Sodium	0.30	3.1	3.9	5.6	19.0	38
	Alkalinity (as $CaCO_3$)	10.0	30.0	46.5	66.0	280	38
	Chloride	0.40	0.80	1.4	4.5	19.0	37
	Fluoride	0.10	0.10	0.10	0.30	5.1	37
	Silica	19.0	33.0	40.0	45.8	120	38
	Sulfate	0.80	3.3	5.5	8.4	17.0	38
	Total dissolved solids	65.0	87.5	99.5	143	340	38
	Ammonia (as N)	--	0.080	0.11	0.29	--	16
	Nitrate+nitrite (as N)	--	0.11	0.32	3.8	--	28
	Phosphorus, unfiltered (as P)	--	0.15	0.22	0.48	--	28
	Boron	--	10.0	20.0	50.0	--	5
	Iron	--	20.0	35.0	120	--	38
	Manganese	--	10.0	20.0	50.0	--	15

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in Quaternary hydrothermal deposits	pH (standard units)	2.6	--	--	--	--	1
	Specific conductance (µS/cm)	1,240	--	--	--	--	1
	Hardness (as $CaCO_3$)	8.0	--	--	--	--	1
	Calcium	3.0	--	--	--	--	1
	Magnesium	0.25	--	--	--	--	1
	Potassium	19.6	--	--	--	--	1
	Sodium-adsorption ratio (unitless)	13.0	--	--	--	--	1
	Sodium	83.9	--	--	--	--	1
	Chloride	54.5	--	--	--	--	1
	Silica	115	--	--	--	--	1
	Sulfate	283	--	--	--	--	1
	Total dissolved solids	568	--	--	--	--	1
Quaternary glacial-deposit aquifers	pH (standard units)	5.6	6.1	6.4	7.7	8.0	17
	Specific conductance (µS/cm)	88.0	242	310	379	1,320	17
	Hardness (as $CaCO_3$)	6.0	19.0	34.0	95.0	590	17
	Calcium	1.9	5.5	10.0	24.0	130	17
	Magnesium	0.31	1.2	2.1	8.9	62.0	17
	Potassium	2.2	3.6	6.2	11.0	29.0	17
	Sodium-adsorption ratio (unitless)	1.5	3.1	3.8	4.6	8.3	10
	Sodium	7.0	15.0	40.0	47.0	58.0	17
	Alkalinity (as $CaCO_3$)	30.0	39.0	62.0	130	333	17
	Chloride	1.5	2.5	22.0	36.0	60.0	17
	Fluoride	0.70	1.2	1.6	2.4	6.2	17
	Silica	3.0	34.0	45.0	53.0	89.0	17
	Sulfate	1.0	5.0	6.6	15.0	390	17
	Total dissolved solids	112	164	223	237	933	17
	Ammonia (as N)	--	0.15	0.35	1.5	--	8
	Nitrate+nitrite (as N)	--	0.70	3.7	11.0	--	10
	Phosphorus, unfiltered (as P)	--	0.28	2.5	8.8	--	10
	Boron	--	20.0	30.0	60.0	--	5
	Iron	--	70.0	225	430	--	14
	Manganese	--	270	550	1,290	--	8

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Aquifers in rhyolite flows, tuff, and intrusive igneous rocks	pH (standard units)	5.4	5.4	5.6	6.6	8.0	10
	Specific conductance (µS/cm)	42.0	48.0	72.0	214	586	10
	Hardness (as $CaCO_3$)	11.0	12.0	15.0	21.5	29.0	10
	Calcium	3.7	4.0	4.5	7.6	10.0	10
	Magnesium	0.17	0.48	0.63	0.84	1.7	9
	Potassium	1.9	3.0	3.2	6.0	27.2	10
	Sodium-adsorption ratio (unitless)	0.30	0.40	0.40	2.0	32.0	8
	Sodium	2.1	3.2	4.1	35.3	240	10
	Alkalinity (as $CaCO_3$)	12.0	16.0	18.5	50.5	136	10
	Chloride	0.40	0.43	0.85	11.2	329	10
	Fluoride	5.2	--	--	--	7.8	2
	Silica	15.8	26.0	39.0	72.0	111	10
	Sulfate	1.4	1.7	1.9	6.0	115	10
	Total dissolved solids	40.0	48.3	93.0	214	808	10
	Barium	--	0.90	3.1	4.5	--	8
	Iron	--	<0.001	0.015	40.0	--	9
	Lithium	--	10.0	15.0	85.0	--	8
	Strontium	--	10.0	10.0	20.0	--	3

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Yellowstone Group aquifers	pH (standard units)	3.0	5.5	5.8	6.7	8.1	26
	Specific conductance (µS/cm)	25.0	98.0	304	1,220	2,440	20
	Hardness (as $CaCO_3$)	5.0	11.3	19.0	25.0	130	26
	Calcium	1.8	4.4	6.0	9.5	44.3	26
	Magnesium	0.01	0.14	0.52	1.1	5.6	26
	Potassium	1.2	3.5	12.1	31.0	53.0	26
	Sodium-adsorption ratio (unitless)	0.30	1.2	5.8	38.3	63.0	26
	Sodium	1.7	15.0	87.1	296	478	26
	Alkalinity (as $CaCO_3$)	11.0	33.3	76.0	116	270	20
	Chloride	0.20	2.4	32.1	395	827	26
	Silica	8.1	54.5	165	769	1,050	26
	Sulfate	1.2	2.7	19.8	64.4	286	26
	Total dissolved solids	43.0	136	563	1,660	2,130	26
	Aluminum	--	<0.001	0.010	198	--	22
	Antimony	--	<0.001	<0.001	41.0	--	18
	Arsenic	--	0.012	21.3	890	--	18
	Barium	--	3.0	10.5	41.0	--	22
	Boron	--	110	1,470	7,240	--	22
	Bromine	--	0.034	0.15	1.2	--	26
	Iron	--	<0.001	20.0	80.0	--	23
	Lithium	--	90.0	685	3,040	--	24
	Manganese	--	30.0	40.0	165	--	12
	Molybdenum	--	<0.001	4.5	71.0	--	18
	Strontium	--	10.0	20.0	30.0	--	21
	Zinc	--	10.0	15.0	20.0	--	4

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Absaroka Volcanic Supergroup aquifers	pH (standard units)	6.5	7.3	7.6	7.8	8.1	10
	Specific conductance (µS/cm)	156	197	308	379	412	8
	Hardness (as $CaCO_3$)	28.0	29.0	75.5	123	150	8
	Calcium	6.0	8.1	14.0	30.8	37.0	10
	Magnesium	1.0	2.6	4.5	9.0	13.0	10
	Potassium	0.30	0.63	1.3	1.8	2.2	10
	Sodium-adsorption ratio (unitless)	0.50	1.2	2.5	2.8	6.2	7
	Sodium	7.3	29.0	32.0	42.3	76.0	10
	Alkalinity (as $CaCO_3$)	73.0	102	133	152	203	10
	Chloride	0.80	0.93	1.2	3.5	4.0	10
	Fluoride	0.20	0.20	0.20	0.38	0.55	10
	Silica	7.7	21.0	25.0	27.3	31.0	8
	Sulfate	1.2	10.0	11.5	16.3	77.0	10
	Total dissolved solids	101	141	176	229	265	10
	Nitrate+nitrite (as N)	--	0.20	0.25	0.31	--	7
	Phosphorus, unfiltered (as P)	--	0.012	0.13	0.14	--	7
	Arsenic	--	0.69	1.6	3.9	--	7
	Boron	--	10.0	25.0	70.0	--	6
	Iron	--	10.0	13.0	110	--	6
	Manganese	--	1.0	1.0	16.0	--	5
	Selenium	--	0.58	1.2	2.5	--	7
Willwood aquifer	pH (standard units)	7.3	--	8.2	--	8.6	3
	Specific conductance (µS/cm)	371	--	519	--	678	3
	Hardness (as $CaCO_3$)	130	--	170	--	290	3
	Calcium	36.0	--	46.0	--	82.0	3
	Magnesium	10.0	--	14.0	--	20.0	3
	Potassium	0.90	--	1.1	--	2.2	3
	Sodium-adsorption ratio (unitless)	1.0	--	1.2	--	1.9	3
	Sodium	33.0	--	38.0	--	58.0	3
	Alkalinity (as $CaCO_3$)	192	--	241	--	328	3
	Chloride	1.6	--	2.0	--	2.0	3
	Fluoride	0.20	--	0.20	--	0.20	3
	Silica	16.0	--	24.0	--	28.0	3
	Sulfate	11.0	--	20.0	--	39.0	3
	Total dissolved solids	220	--	326	--	398	3

Appendix E3. Summary statistics for environmental water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[For constituents with censored values, a minimum value cannot be determined; consequently, a resistant measure of data spread, the 25th and 75th percentiles are presented (rather than minimum and maximum values) to characterize the data spread. --, not applicable; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Paleozoic lithostratigraphic units							
Madison aquifer	pH (standard units)	8.2	--	--	--	--	1
	Specific conductance (µS/cm)	246	--	--	--	--	1
	Hardness (as $CaCO_3$)	130	--	--	--	--	1
	Calcium	30.0	--	--	--	--	1
	Magnesium	14.0	--	--	--	--	1
	Potassium	0.40	--	--	--	--	1
	Sodium	0.60	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	152	--	--	--	--	1
	Chloride	0.20	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	6.6	--	--	--	--	1
	Sulfate	11.0	--	--	--	--	1
	Total dissolved solids	138	--	--	--	--	1

Appendix F1

Summary statistics for produced water samples, Wind River Basin, Wyoming

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Cenozoic lithostratigraphic units							
Wind River aquifer	pH (standard units)	5.9	7.5	7.9	8.2	8.9	45
	Calcium	3.0	15.0	38.0	135	8,770	47
	Magnesium	3.0	5.5	13.0	29.5	131	43
	Potassium	3.0	19.3	69.0	115	1,910	30
	Sodium	344	602	938	1,610	5,700	47
	Bicarbonate	80.0	500	902	1,200	3,360	47
	Carbonate	10.0	13.3	24.5	58.3	100	6
	Chloride	17.0	310	853	1,180	24,000	47
	Sulfate	2.0	10.0	63.0	658	5,140	43
	Total dissolved solids	1,060	1,820	2,730	4,860	38,800	47
	Iron	1,170	4,650	12,100	47,200	191,000	19
Fort Union aquifer	pH (standard units)	4.5	7.5	8.0	8.4	10.2	384
	Calcium	1.0	16.7	26.5	45.8	18,400	378
	Magnesium	1.0	5.0	8.0	14.0	680	367
	Potassium	5.8	48.0	85.0	103	27,900	274
	Sodium	290	1,770	2,790	3,610	20,700	386
	Bicarbonate	146	1,770	2,490	3,210	14,800	382
	Carbonate	1.0	23.5	50.0	105	420	71
	Chloride	13.6	983	2,800	4,000	43,000	386
	Sulfate	1.0	7.0	26.0	152	6,820	335
	Total dissolved solids	872	5,040	7,560	9,540	69,100	386
	Copper	10	--	--	--	--	1
	Iron	10	1,200	7,270	42,000	2,370,000	92
	Manganese	90	--	--	--	--	1
	Nickel	70	--	--	--	--	1
	Selenium	10	--	--	--	--	1
	Zinc	20	--	--	--	--	1
Hydrogeologic units in Mesozoic lithostratigraphic units							
Lance aquifer	pH (standard units)	5.8	7.6	8.0	8.3	9.1	80
	Calcium	3.7	19.0	32.5	70.9	33,300	80
	Magnesium	1.0	5.0	9.0	24.0	835	77
	Potassium	7.0	20.5	29.0	80.0	10,300	34
	Sodium	689	1,940	2,580	3,050	7,910	80
	Bicarbonate	122	1,300	2,000	2,530	4,270	80
	Carbonate	34.0	--	36.0	--	336	3

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Lance aquifer—continued	Chloride	152	1,680	2,680	4,000	71,000	80
	Silica	45.0	--	53.0	--	58.0	3
	Sulfate	4.0	24.0	101	252	2,850	71
	Total dissolved solids	1,680	5,760	6,720	8,840	113,000	80
	Barium	5,000	--	6,000	--	11,000	3
	Iron	210	3,130	28,000	59,900	168,000	23
Meeteetse–Lewis confining unit (both samples from Lewis Shale)	pH (standard units)	8.3	--	--	--	8.4	2
	Calcium	17.0	--	--	--	79.0	2
	Magnesium	9.0	--	--	--	53.0	2
	Potassium	25.0	--	--	--	40.0	2
	Sodium	1,180	--	--	--	2,160	2
	Bicarbonate	891	--	--	--	4,030	2
	Chloride	100	--	--	--	530	2
	Sulfate	195	--	--	--	2,130	2
	Total dissolved solids	4,020	--	--	--	5,250	2
Mesaverde aquifer	pH (standard units)	5.6	7.0	7.9	8.2	8.9	41
	Calcium	4.0	24.5	45.5	91.0	1,050	48
	Magnesium	1.0	7.0	11.5	30.8	501	46
	Potassium	5.0	39.5	70.0	119	407	31
	Sodium	5.0	1,060	1,700	2,290	5,890	47
	Bicarbonate	90.9	947	1,410	2,180	4,580	48
	Carbonate	72.0	--	--	--	--	1
	Chloride	16.0	206	1,110	2,260	8,700	48
	Sulfate	2.0	15.0	167	1,100	4,500	42
	Total dissolved solids	1,710	3,260	4,710	6,930	15,300	48
	Aluminum	1,060	--	--	--	--	1
	Barium	2,430	--	--	--	--	1
	Iron	1,700	3,680	9,860	38,400	400,000	12
	Manganese	630	--	--	--	--	1
	Molybdenum	10	--	--	--	--	1
	Lead	40	--	--	--	--	1
	Selenium	10	--	--	--	--	1
	Zinc	120	--	--	--	--	1
Cody confining unit	pH (standard units)	5.4	7.2	8.2	8.5	9.5	36
	Calcium	2.0	9.0	17.0	50.0	1,700	40
	Magnesium	0.89	3.0	6.0	14.0	264	38

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cody confining unit—continued	Potassium	3.0	16.0	46.0	108	1,220	29
	Sodium	118	1,390	1,980	3,240	8,580	40
	Bicarbonate	73.5	456	1,320	1,920	5,100	40
	Carbonate	43.0	54.3	89.0	135	181	4
	Chloride	20.0	1,130	2,480	4,180	12,900	40
	Sulfate	4.0	10.0	60.0	99.0	1,600	25
	Total dissolved solids	299	3,490	5,620	8,070	24,000	40
	Iron	600	2,860	19,000	21,000	40,800	5
Frontier aquifer	pH (standard units)	5.9	7.7	8.2	8.4	9.0	33
	Calcium	0.60	14.3	30.0	55.3	6,630	38
	Magnesium	0.90	6.1	16.0	29.5	467	35
	Potassium	4.8	31.5	55.0	210	340	19
	Sodium	58.7	2,240	3,760	4,540	9,200	38
	Bicarbonate	216	1,160	1,710	3,280	7,090	38
	Carbonate	3.0	51.0	276	288	336	5
	Chloride	2.0	2,510	3,560	6,260	27,000	38
	Sulfate	3.0	16.0	44.0	142	1,400	33
	Total dissolved solids	219	6,190	9,590	12,300	43,700	38
	Iron	40	1,980	4,350	64,800	241,000	4
Muddy Sandstone aquifer	pH (standard units)	5.8	7.9	8.2	8.3	8.5	11
	Calcium	3.0	10.8	17.0	35.8	326	12
	Magnesium	1.0	4.5	8.5	18.0	68.0	12
	Potassium	10.0	10.0	12.5	18.5	29.0	4
	Sodium	443	1,250	2,220	2,810	3,910	12
	Bicarbonate	451	752	2,660	3,650	6,600	11
	Chloride	68.0	120	883	3,260	4,170	12
	Sulfate	4.0	36.0	163	1,210	1,860	11
	Total dissolved solids	1,220	3,510	6,060	7,890	9,610	12
	Iron	11,000	--	--	--	--	1
Cloverly aquifer	pH (standard units)	7.6	8.0	8.2	8.5	8.9	17
	Calcium	1.5	12.0	19.0	40.0	309	19
	Magnesium	2.0	4.0	6.5	12.3	36.0	16
	Potassium	15.0	17.5	22.0	42.9	718	6
	Sodium	354	1,520	2,130	3,790	10,800	19
	Bicarbonate	165	1,300	1,590	1,830	5,390	19
	Carbonate	50.0	--	--	--	--	1

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Cloverly aquifer—continued	Chloride	12.0	953	2,400	4,510	13,200	19
	Sulfate	5.0	202	523	751	2,250	19
	Total dissolved solids	1,110	4,000	5,370	9,650	30,000	19
	Iron	50	--	--	--	8,200	2
Morrison confining unit	pH (standard units)	6.9	6.9	7.5	7.8	8.3	5
	Calcium	20.0	32.0	37.0	102	539	9
	Magnesium	9.0	11.0	32.0	35.0	140	7
	Potassium	28.0	--	--	--	30.0	2
	Sodium	320	395	1,920	3,340	4,630	9
	Bicarbonate	268	525	738	1,110	1,310	9
	Chloride	13.0	1,410	2,460	4,560	5,740	9
	Sulfate	6.0	365	555	963	1,250	9
	Total dissolved solids	1,090	2,930	4,960	9,440	12,000	9
Sundance aquifer	pH (standard units)	5.1	7.0	7.6	7.7	8.0	4
	Calcium	20.0	127	277	503	537	8
	Magnesium	5.0	23.0	54.0	84.0	108	7
	Sodium	303	2,080	4,660	7,000	10,100	8
	Bicarbonate	219	335	461	629	845	8
	Chloride	16.0	2,450	3,290	6,710	10,600	8
	Sulfate	5.0	1,230	4,990	7,750	7,960	8
	Total dissolved solids	1,760	5,550	14,500	20,900	29,500	8
Nugget aquifer	pH (standard units)	5.8	7.5	7.9	8.2	8.6	33
	Calcium	10.0	50.8	194	571	65,200	34
	Magnesium	3.0	12.0	30.0	125	305	33
	Potassium	5.0	27.5	77.0	160	920	15
	Sodium	370	1,240	2,010	8,310	15,100	34
	Bicarbonate	60.0	288	376	623	1,660	34
	Chloride	36.0	258	636	10,800	136,000	34
	Sulfate	91.0	1,340	3,090	5,230	10,100	34
	Total dissolved solids	1,200	4,310	6,520	29,700	217,000	34
	Iron	16,000	--	--	--	23,000	2
Chugwater aquifer	pH (standard units)	5.0	7.5	8.0	8.4	8.9	153
	Calcium	3.0	115	320	514	8,900	175
	Magnesium	1.0	18.5	71.0	114	2,700	175

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Chugwater aquifer—continued	Potassium	5.0	16.8	49.5	90.0	906	92
	Sodium	10.0	605	1,510	3,300	15,900	175
	Bicarbonate	15.0	516	783	1,490	9,520	174
	Chloride	10.0	160	675	2,440	41,000	175
	Sulfate	2.0	410	1,500	2,910	11,400	171
	Total dissolved solids	1,010	3,010	5,330	11,300	72,100	175
	Barium	100	--	--	--	130	2
	Iron	100	--	2,000	--	104,000	3
	Manganese	50	--	--	--	--	1
	Strontium	3,500	--	--	--	--	1
Dinwoody confining unit	pH (standard units)	6.5	--	8.0	--	8.0	3
	Calcium	185	437	546	590	776	5
	Magnesium	40.0	59.0	122	150	163	5
	Potassium	32.0	--	--	--	--	1
	Sodium	106	250	658	1,650	4,140	5
	Bicarbonate	256	456	646	1,020	1,170	5
	Chloride	34.0	56.0	164	181	2,530	5
	Sulfate	741	1,570	3,450	3,560	6,020	5
	Total dissolved solids	1,540	2,740	5,320	6,970	14,100	5
Hydrogeologic units in Paleozoic lithostratigraphic units							
Phosphoria aquifer and confining unit	pH (standard units)	5.0	7.2	7.7	8.2	8.9	135
	Calcium	16.0	190	353	579	30,100	146
	Magnesium	3.0	45.3	72.7	154	7,940	142
	Potassium	3.0	14.8	37.0	94.0	995	68
	Sodium	9.0	483	1,230	3,510	42,900	146
	Bicarbonate	59.0	295	498	988	10,100	146
	Chloride	8.0	137	528	2,740	95,000	146
	Sulfate	10.0	875	1,950	4,720	15,000	146
	Total dissolved solids	372	2,860	5,810	12,200	155,000	146
Tensleep aquifer	pH (standard units)	5.2	7.2	7.7	8.2	8.9	89
	Calcium	16.0	146	248	385	2,840	114
	Magnesium	4.0	36.0	55.5	76.8	817	110
	Potassium	10.0	39.0	50.5	71.5	232	16
	Sodium	9.0	373	611	1,100	7,670	114
	Bicarbonate	92.0	291	500	732	4,290	113
	Carbonate	20.0	--	--	--	--	1

Appendix F1. Summary statistics for produced water samples, Wind River Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Tensleep aquifer—continued	Chloride	3.6	130	210	603	12,400	113
	Sulfate	3.0	965	1,300	1,640	8,720	113
	Total dissolved solids	167	2,420	2,930	4,370	25,600	114
	Iron	1,270	--	--	--	--	1
Amsden aquifer	pH (standard units)	8.2	--	--	--	--	1
	Calcium	123	--	--	--	--	1
	Magnesium	34.0	--	--	--	--	1
	Sodium	1,900	--	--	--	--	1
	Bicarbonate	574	--	--	--	--	1
	Chloride	416	--	--	--	--	1
	Sulfate	3,290	--	--	--	--	1
	Total dissolved solids	6,100	--	--	--	--	1
Madison aquifer	pH (standard units)	5.7	7.1	7.7	8.1	8.9	62
	Calcium	32.0	97.3	165	277	4,090	64
	Magnesium	4.0	17.0	28.0	68.5	2,210	64
	Potassium	2.5	26.0	42.8	62.3	150	38
	Sodium	1.9	363	499	683	8,330	64
	Bicarbonate	90.0	244	299	403	1,650	62
	Chloride	3.6	221	470	934	18,500	64
	Sulfate	29.0	481	576	753	3,070	64
	Total dissolved solids	291	1,630	2,040	3,160	30,600	64
	Arsenic	1,120	--	--	--	--	1
	Barium	100	--	100	--	100	3
	Iron	100	100	100	200	500	4
	Manganese	30	30	30	30	60	5
	Strontium	3,000	--	3,000	--	3,000	3
Flathead aquifer	pH (standard units)	7.5	--	--	--	--	1
	Calcium	144	--	--	--	--	1
	Magnesium	7.0	--	--	--	--	1
	Potassium	15.0	--	--	--	--	1
	Sodium	714	--	--	--	--	1
	Bicarbonate	268	--	--	--	--	1
	Chloride	280	--	--	--	--	1
	Sulfate	1,300	--	--	--	--	1
	Total dissolved solids	2,590	--	--	--	--	1

Appendix F2

Summary statistics for produced water samples, Bighorn Basin, Wyoming

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Cenozoic lithostratigraphic units							
Fort Union aquifer	pH (standard units)	8.2	--	--	--	--	1
	Calcium	18.0	--	--	--	--	1
	Magnesium	5.0	--	--	--	--	1
	Sodium	540	--	--	--	--	1
	Bicarbonate	280	--	--	--	--	1
	Chloride	52.0	--	--	--	--	1
	Sulfate	786	--	--	--	--	1
	Total dissolved solids	1,610	--	--	--	--	1
Hydrogeologic units in Mesozoic lithostratigraphic units							
Lance aquifer	pH (standard units)	8.4	--	--	--	8.6	2
	Calcium	10.0	--	11.0	--	116	3
	Magnesium	2.0	--	3.0	--	66.0	3
	Sodium	470	--	684	--	1,430	3
	Bicarbonate	605	--	732	--	805	3
	Chloride	92.0	--	245	--	392	3
	Sulfate	202	--	241	--	2,720	3
	Total dissolved solids	1,210	--	1,760	--	4,880	3
Meteetsee aquifer and confining unit	pH (standard units)	7.6	--	8.4	--	8.6	3
	Calcium	0.30	--	26.8	--	61.7	3
	Magnesium	4.2	--	--	--	6.5	2
	Potassium	2.0	--	2.0	--	5.0	3
	Sodium-adsorption ratio (unitless)	29.5	--	42.4	--	460	3
	Sodium	623	--	864	--	1,310	3
	Bicarbonate	1,120	--	1,580	--	2,040	3
	Chloride	374	--	380	--	792	3
	Fluoride	1.5	--	--	--	5.7	2
	Total dissolved solids	2,150	--	2,300	--	5,520	3
	Iron	800	--	--	--	--	1
Mesaverde aquifer	pH (standard units)	7.3	7.6	7.8	8.2	8.7	21
	Calcium	0.30	3.8	12.0	35.0	236	21
	Magnesium	0.10	1.3	3.0	14.0	79.0	19
	Potassium	1.0	4.0	5.5	10.4	17.0	18
	Sodium-adsorption ratio (unitless)	20.8	58.5	81.4	117	285	10

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mesaverde aquifer—continued	Sodium	115	663	776	1,040	2,110	21
	Bicarbonate	281	929	1,370	1,950	3,850	21
	Carbonate	48.0	48.0	52.0	66.0	96.0	4
	Chloride	14.0	201	292	534	1,930	20
	Fluoride	0.10	0.85	3.1	5.2	5.6	4
	Sulfate	1.0	3.0	39.0	204	1,680	15
	Total dissolved solids	965	2,050	2,390	2,790	7,400	21
	Boron	1,300	1,800	2,100	2,400	2,500	4
	Iron	430	990	2,400	3,100	4,600	6
Cody confining unit	pH (standard units)	7.8	8.1	8.6	8.7	8.8	5
	Calcium	6.0	18.0	40.0	44.0	44.0	5
	Magnesium	10.0	11.0	16.0	16.0	21.0	5
	Potassium	38.0	--	40.0	--	62.0	3
	Sodium	937	982	1,060	1,160	2,660	5
	Bicarbonate	1,290	1,360	1,760	1,830	2,340	5
	Chloride	52.0	52.0	52.0	450	3,200	5
	Sulfate	51.0	109	293	590	1,190	5
	Total dissolved solids	2,440	2,710	2,940	3,180	6,750	5
Frontier aquifer	pH (standard units)	6.5	7.8	8.1	8.4	9.1	128
	Calcium	0.20	10.3	19.0	44.9	549	126
	Magnesium	1.0	3.1	6.0	13.3	1,190	116
	Potassium	2.0	9.0	14.0	25.8	410	68
	Sodium-adsorption ratio (unitless)	49.1	128	169	221	445	29
	Sodium	481	1,510	2,520	3,520	29,600	133
	Bicarbonate	163	1,080	1,590	2,420	8,940	127
	Carbonate	76.0	--	76.0	--	144	3
	Chloride	20.0	380	2,140	4,750	39,800	133
	Fluoride	1.4	1.9	2.9	3.5	6.3	12
	Sulfate	6.0	44.5	171	691	19,500	83
	Total dissolved solids	1,470	3,920	6,630	9,600	81,800	133
	Boron	1,300	2,100	2,500	3,300	200,000	5
	Barium	200	--	--	--	200	2
	Iron	340	1,100	2,700	3,000	203,000	13
	Strontium	900	--	--	--	--	1

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Mowry confining unit	pH (standard units)	8.2	8.3	8.4	8.5	8.6	5
	Calcium	4.0	9.3	13.5	21.5	38.0	4
	Magnesium	1.0	--	8.0	--	14.0	3
	Potassium	2.0	--	--	--	--	1
	Sodium	455	757	770	858	3,300	5
	Bicarbonate	927	939	1,670	1,880	6,630	5
	Chloride	59.0	63.0	80.0	760	1,290	5
	Sulfate	4.0	--	15.0	--	67.0	3
	Total dissolved solids	1,080	1,790	1,820	2,160	7,950	5
Muddy Sandstone aquifer	pH (standard units)	4.2	7.5	8.0	8.4	8.8	21
	Calcium	3.0	10.5	34.0	55.5	6,900	19
	Magnesium	1.0	3.8	6.0	17.3	1,140	20
	Potassium	3.0	7.3	26.0	124	3,880	10
	Sodium	139	810	1,710	2,370	4,260	23
	Bicarbonate	318	970	1,320	1,950	3,880	22
	Carbonate	222	--	--	--	--	1
	Chloride	10.0	93.0	415	1,630	31,000	23
	Sulfate	16.0	134	364	501	4,530	22
	Total dissolved solids	1,040	2,050	4,810	6,550	47,300	23
	Barium	100	--	--	--	600	2
	Iron	54,700	--	--	--	--	1
	Strontium	100	--	--	--	--	1
Cloverly aquifer	pH (standard units)	6.3	8.2	8.2	8.4	8.7	25
	Calcium	4.0	7.0	11.5	28.0	729	24
	Magnesium	1.0	3.0	6.4	13.8	261	22
	Potassium	3.0	6.0	8.0	12.5	59.0	11
	Sodium	325	994	1,280	1,940	4,430	27
	Bicarbonate	598	1,100	1,660	2,100	3,050	27
	Carbonate	24.0	--	--	--	24.0	2
	Chloride	32.0	188	520	1,500	6,300	27
	Sulfate	8.0	114	370	1,690	3,560	25
	Total dissolved solids	1,320	2,690	4,290	5,320	11,500	27
	Strontium	500	--	--	--	--	1

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Morrison confining unit	pH (standard units)	7.4	7.6	8.0	8.4	8.8	10
	Calcium	12.0	19.0	79.0	116	716	9
	Magnesium	5.0	9.5	18.0	29.3	195	8
	Potassium	5.0	--	--	--	12.0	2
	Sodium	757	926	2,680	4,890	6,880	10
	Bicarbonate	688	725	1,030	1,330	1,690	10
	Carbonate	24.0	--	--	--	72.0	2
	Chloride	48.0	240	3,490	6,870	10,500	10
	Sulfate	2.0	129	248	672	2,710	10
	Total dissolved solids	2,270	2,710	7,130	12,800	18,700	10
Sundance confining unit and aquifer	pH (standard units)	7.0	8.1	8.2	8.4	8.7	9
	Calcium	4.0	4.0	8.0	108	496	9
	Magnesium	1.0	1.5	9.0	19.0	36.0	7
	Potassium	1.0	--	2.0	--	23.0	3
	Sodium	859	930	1,260	1,410	4,790	9
	Bicarbonate	781	840	956	1,550	2,020	9
	Carbonate	13.0	--	--	--	--	1
	Chloride	308	328	560	1,310	1,960	9
	Sulfate	27.0	62.0	785	1,630	6,990	9
	Total dissolved solids	2,280	2,540	3,080	4,260	14,300	9
	Strontium	200	--	--	--	--	1
Chugwater aquifer	pH (standard units)	6.6	7.4	7.9	8.2	8.9	89
	Calcium	4.0	325	495	620	1,270	99
	Magnesium	1.0	74.3	112	170	519	98
	Potassium	5.0	36.3	67.0	94.5	185	26
	Sodium	84.0	1,910	7,970	12,300	19,900	99
	Bicarbonate	42.0	281	605	1,520	5,560	98
	Carbonate	2.0	--	--	--	300	2
	Chloride	21.0	955	6,900	13,400	27,000	99
	Sulfate	62.0	2,790	6,420	8,900	13,300	99
	Total dissolved solids	1,170	7,150	24,100	35,100	57,500	99
	Iron	4,100	--	--	--	--	1
	Strontium	400	--	--	--	--	1

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Dinwoody confining unit	pH (standard units)	7.9	--	--	--	--	1
	Calcium	1,600	--	--	--	--	1
	Magnesium	612	--	--	--	--	1
	Potassium	55.0	--	--	--	--	1
	Sodium	553	--	--	--	--	1
	Bicarbonate	1,160	--	--	--	--	1
	Chloride	3,880	--	--	--	--	1
	Sulfate	1,320	--	--	--	--	1
	Total dissolved solids	8,590	--	--	--	--	1
Hydrogeologic units in Paleozoic lithostratigraphic units							
Phosphoria aquifer and confining unit	pH (standard units)	4.7	7.2	7.8	8.2	9.1	409
	Calcium	3.0	339	476	593	35,000	503
	Magnesium	1.0	78.0	128	182	22,600	497
	Potassium	2.0	40.0	80.0	175	420	121
	Sodium	23.0	923	1,670	3,090	23,400	504
	Bicarbonate	10.0	693	1,120	1,580	25,600	503
	Carbonate	17.0	42.0	156	761	1,370	10
	Chloride	7.0	296	608	1,700	147,000	504
	Sulfate	35.0	1,770	3,010	4,760	27,800	503
	Total dissolved solids	1,080	4,870	7,200	11,600	220,000	505
	Barium	100	--	--	--	8,000	2
	Lithium	2,000	--	--	--	4,000	2
	Iron	70	570	1,300	3,800	612,000	16
	Strontium	5,100	--	--	--	9,800	2
Tensleep aquifer	pH (standard units)	3.5	7.2	7.6	8.0	8.9	443
	Calcium	13.0	327	506	608	6,600	504
	Magnesium	2.0	76.0	116	154	2,740	500
	Potassium	4.0	19.0	36.0	109	341	61
	Sodium	1.0	174	535	1,110	8,710	502
	Bicarbonate	49.0	381	704	1,220	7,100	502
	Carbonate	9.5	12.0	12.0	24.0	36.0	5
	Chloride	2.0	49.8	168	361	20,300	500
	Silica	6.4	--	--	--	--	1
	Sulfate	6.0	1,350	1,810	2,710	12,500	504
	Total dissolved solids	324	2,780	3,650	5,430	33,700	504
	Barium	90	--	--	--	300	2

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Tensleep aquifer—continued	Bromide	500	--	--	--	--	1
	Iron	390	1,400	32,700	64,700	68,000	4
	Manganese	130	--	--	--	--	1
	Strontium	500	--	--	--	6,300	2
Amsden aquifer	pH (standard units)	6.5	7.0	7.5	8.1	8.7	20
	Calcium	110	212	389	525	9,490	21
	Magnesium	7.0	52.0	92.0	154	5,240	21
	Potassium	14.0	41.8	91.0	137	156	4
	Sodium	11.0	31.0	525	1,400	5,840	21
	Bicarbonate	131	268	714	1,120	1,950	20
	Chloride	16.0	142	300	552	34,700	21
	Sulfate	32.0	752	1,300	2,010	8,220	21
	Total dissolved solids	590	2,570	3,280	4,630	53,500	21
	Barium	100	--	--	--	800	2
	Iron	100	--	--	--	--	1
	Strontium	1,600	--	--	--	5,600	2
Madison aquifer	pH (standard units)	5.5	7.0	7.5	7.8	11.1	175
	Calcium	18.0	310	484	638	15,000	200
	Magnesium	1.0	75.5	124	191	3,100	200
	Potassium	5.0	16.5	32.0	51.0	282	35
	Sodium-adsorption ratio (unitless)	4.5	--	--	--	--	1
	Sodium	2.0	232	391	541	52,600	199
	Bicarbonate	24.0	342	660	1,220	2,900	201
	Carbonate	8.0	--	19.0	--	67.0	3
	Chloride	1.0	161	240	500	85,000	201
	Fluoride	4.1	--	--	--	--	1
	Sulfate	21.6	946	1,470	1,810	4,930	201
	Total dissolved solids	319	2,400	3,370	4,100	142,000	201
	Barium	100	--	--	--	--	1
	Iron	500	--	--	--	19,300	2
	Strontium	8,000	--	--	--	16,000	2

Appendix F2. Summary statistics for produced water samples, Bighorn Basin, Wyoming.—Continued

[--, not applicable. Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Darby aquifer	pH (standard units)	6.8	--	--	--	7.5	2
	Calcium	248	--	--	--	583	2
	Magnesium	114	--	--	--	150	2
	Sodium	304	--	--	--	1,880	2
	Bicarbonate	1,050	--	--	--	1,100	2
	Chloride	220	--	--	--	400	2
	Sulfate	1,500	--	--	--	3,570	2
	Total dissolved solids	3,280	--	--	--	6,760	2
Bighorn aquifer	pH (standard units)	6.4	7.0	7.2	7.5	8.5	9
	Calcium	169	320	453	587	2,900	11
	Magnesium	27.0	93.5	114	181	1,320	11
	Potassium	5.0	--	8.0	--	13.0	3
	Sodium	174	339	452	509	2,350	11
	Bicarbonate	149	391	1,130	1,280	1,490	10
	Chloride	24.0	255	476	945	8,450	11
	Sulfate	342	640	917	1,310	4,360	11
	Total dissolved solids	1,180	2,450	3,460	3,940	14,300	11
Flathead aquifer	pH (standard units)	6.7	7.0	7.2	7.4	7.6	11
	Calcium	20.0	193	334	385	473	13
	Magnesium	5.0	28.3	36.5	43.5	57.0	12
	Potassium	15.0	27.3	61.5	93.5	104	6
	Sodium	499	839	1,140	1,210	4,440	13
	Bicarbonate	44.0	159	161	250	1,040	13
	Chloride	510	856	1,330	1,370	6,850	13
	Sulfate	765	993	1,170	1,280	1,570	13
	Total dissolved solids	2,730	3,430	3,950	4,420	13,300	13
	Strontium	6,700	--	--	--	--	1

Appendix F3

Summary statistics for produced water samples, Absaroka Range and Yellowstone volcanic area, Wyoming

Appendix F3. Summary statistics for produced water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.

[--, not applicable. Values are in milligrams per liter unless otherwise noted]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Mesozoic lithostratigraphic units							
Frontier aquifer	pH (standard units)	6.9	--	--	--	8.3	2
	Calcium	6.0	--	10.0	--	32.0	3
	Potassium	25.0	--	--	--	--	1
	Sodium	577	--	682	--	791	3
	Bicarbonate	561	--	1,270	--	1,830	3
	Chloride	100	--	111	--	530	3
	Sulfate	9.0	--	12.0	--	233	3
	Total dissolved solids	1,420	--	1,800	--	1,870	3
Cloverly aquifer	pH (standard units)	7.8	--	--	--	--	1
	Calcium	18.0	--	--	--	--	1
	Magnesium	2.0	--	--	--	--	1
	Potassium	7.0	--	--	--	--	1
	Sodium	638	--	--	--	--	1
	Bicarbonate	683	--	--	--	--	1
	Chloride	30.0	--	--	--	--	1
	Sulfate	815	--	--	--	--	1
	Total dissolved solids	1,850	--	--	--	--	1
Morrison confining unit and aquifer	pH (standard units)	8.8	--	--	--	--	1
	Calcium	5.0	--	--	--	--	1
	Magnesium	1.0	--	--	--	--	1
	Sodium	507	--	--	--	--	1
	Bicarbonate	596	--	--	--	--	1
	Chloride	24.0	--	--	--	--	1
	Sulfate	530	--	--	--	--	1
	Total dissolved solids	1,390	--	--	--	--	1
Chugwater aquifer	pH (standard units)	7.4	7.7	7.9	8.3	8.4	11
	Calcium	18.0	236	320	354	558	11
	Magnesium	6.0	40.0	68.0	101	140	11
	Potassium	4.0	34.5	45.5	49.8	145	10
	Sodium	599	3,160	4,120	4,500	10,900	11
	Bicarbonate	305	763	1,170	1,540	2,730	11
	Carbonate	48.0	--	--	--	--	1
	Chloride	120	850	1,150	1,450	9,100	11
	Sulfate	308	5,580	6,190	7,550	11,300	11
	Total dissolved solids	1,600	10,700	13,100	14,900	32,800	11

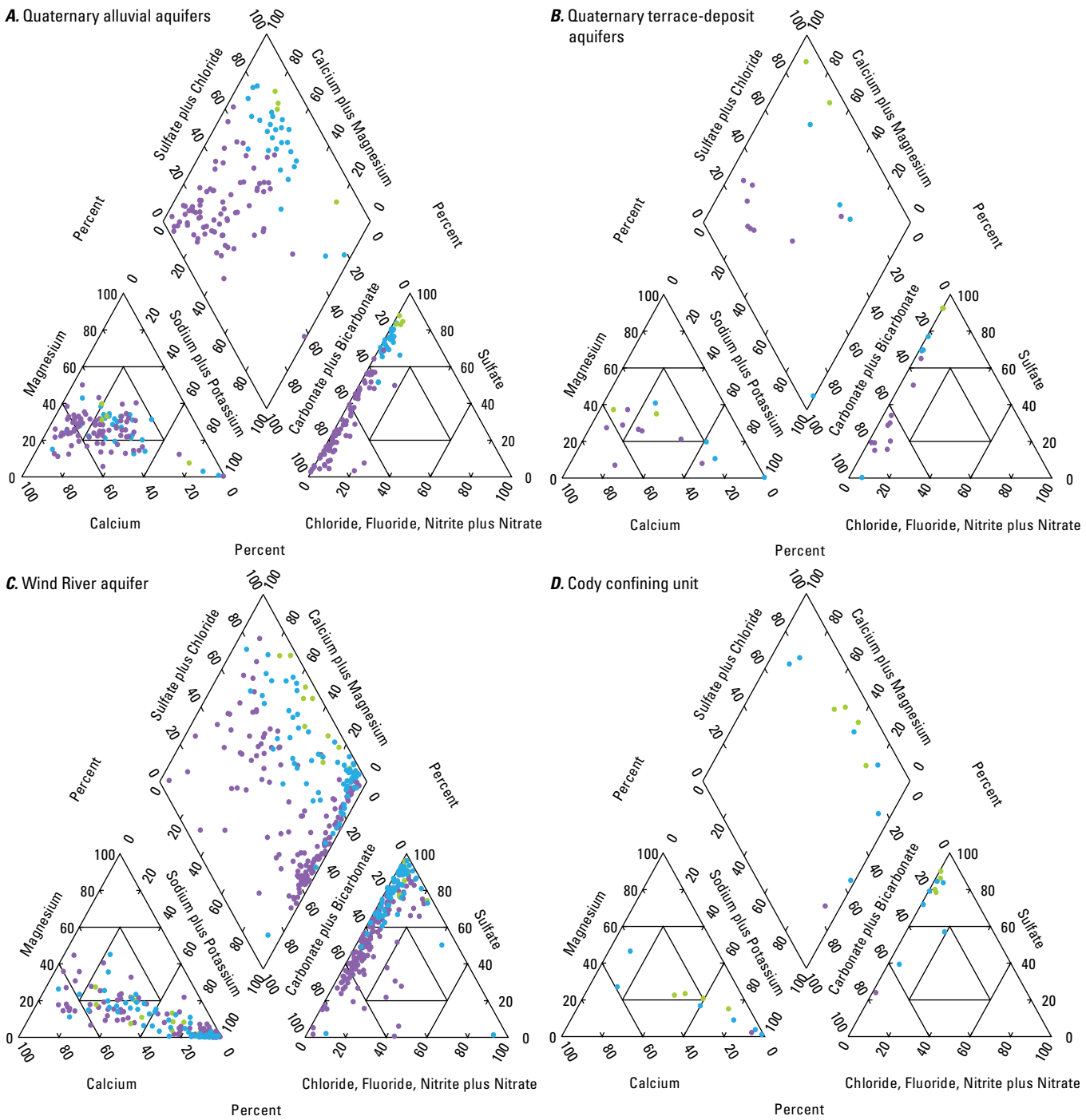
Appendix F3. Summary statistics for produced water samples, Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

[--, not applicable. Values are in milligrams per liter unless otherwise noted]

Hydrogeologic unit	Property or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Hydrogeologic units in Paleozoic lithostratigraphic units							
Phosphoria aquifer and confining unit	pH (standard units)	6.8	7.1	7.5	7.9	8.3	14
	Calcium	68.0	244	501	670	832	14
	Magnesium	44.0	73.5	115	157	199	14
	Potassium	40.0	49.5	65.0	79.0	346	7
	Sodium	117	243	584	693	1,900	14
	Bicarbonate	512	1,060	1,490	1,770	2,100	14
	Carbonate	48.0	--	--	--	--	1
	Chloride	88.0	167	325	380	507	14
	Sulfate	115	728	1,330	2,200	5,000	14
	Total dissolved solids	1,050	2,770	3,810	4,690	8,850	14
Tensleep aquifer	pH (standard units)	7.0	7.3	7.6	7.9	8.2	8
	Calcium	113	310	427	506	919	9
	Magnesium	32.0	85.0	107	119	262	9
	Potassium	35.0	46.3	65.0	87.5	110	4
	Sodium	217	480	915	1,070	2,070	9
	Bicarbonate	554	878	1,760	1,860	3,060	9
	Chloride	40.0	180	200	320	490	9
	Sulfate	185	1,140	1,800	2,600	4,060	9
	Total dissolved solids	1,060	3,860	4,570	4,850	7,950	9
Amsden aquifer	pH (standard units)	7.6	--	--	--	--	1
	Calcium	217	--	--	--	--	1
	Magnesium	75.0	--	--	--	--	1
	Sodium	196	--	--	--	--	1
	Bicarbonate	1,050	--	--	--	--	1
	Chloride	144	--	--	--	--	1
	Sulfate	206	--	--	--	--	1
	Total dissolved solids	1,360	--	--	--	--	1

Appendix G1-1

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming



EXPLANATION

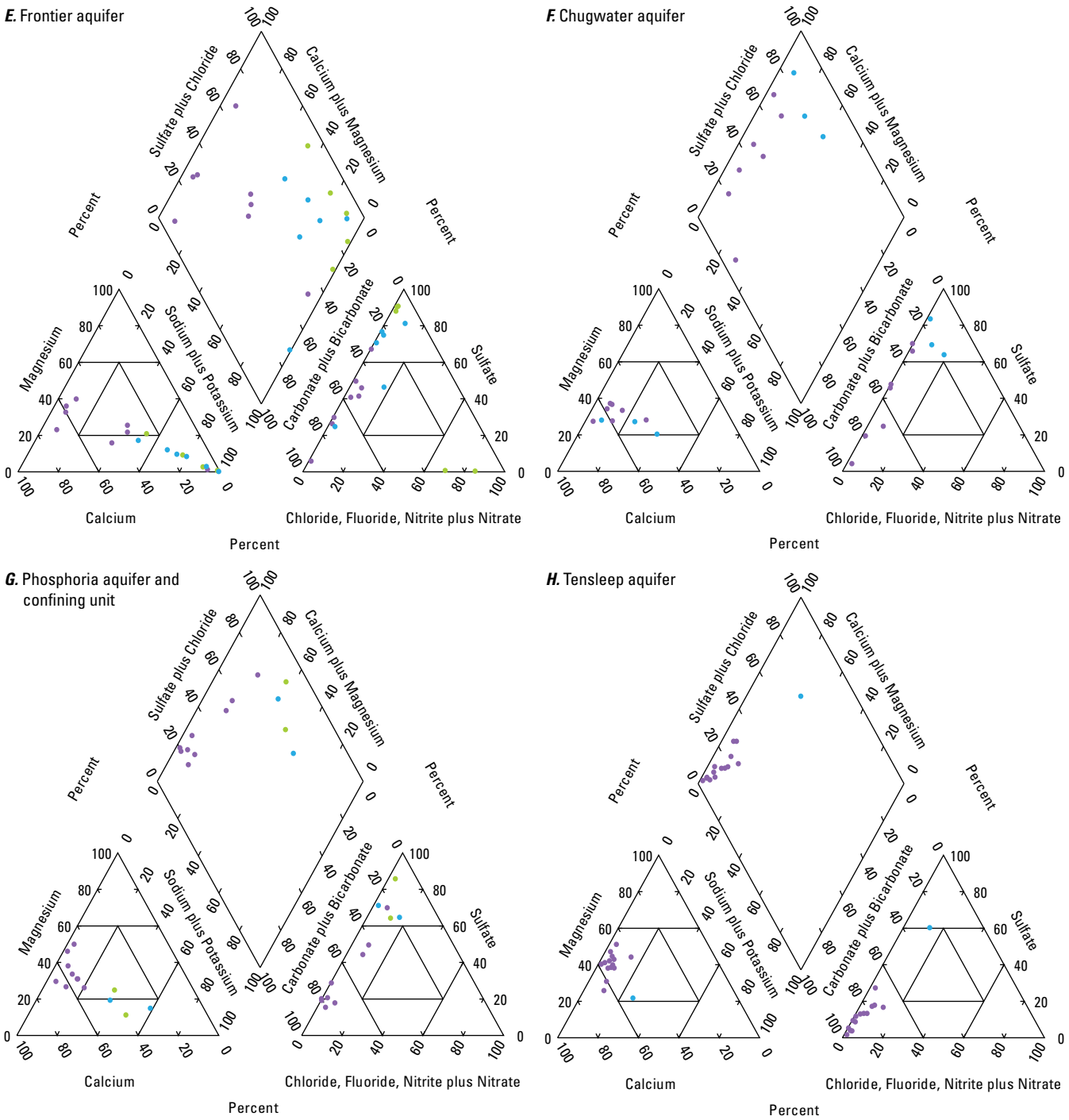
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming.

Appendix G1-2

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- Less than or equal to 999; fresh
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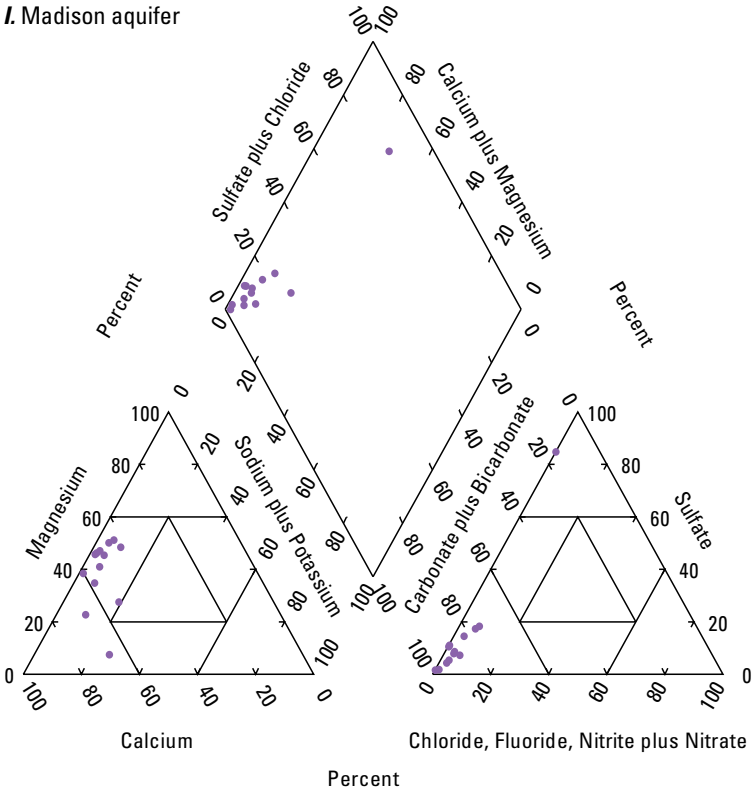
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming.—Continued

Appendix G1-3

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming

I. Madison aquifer



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

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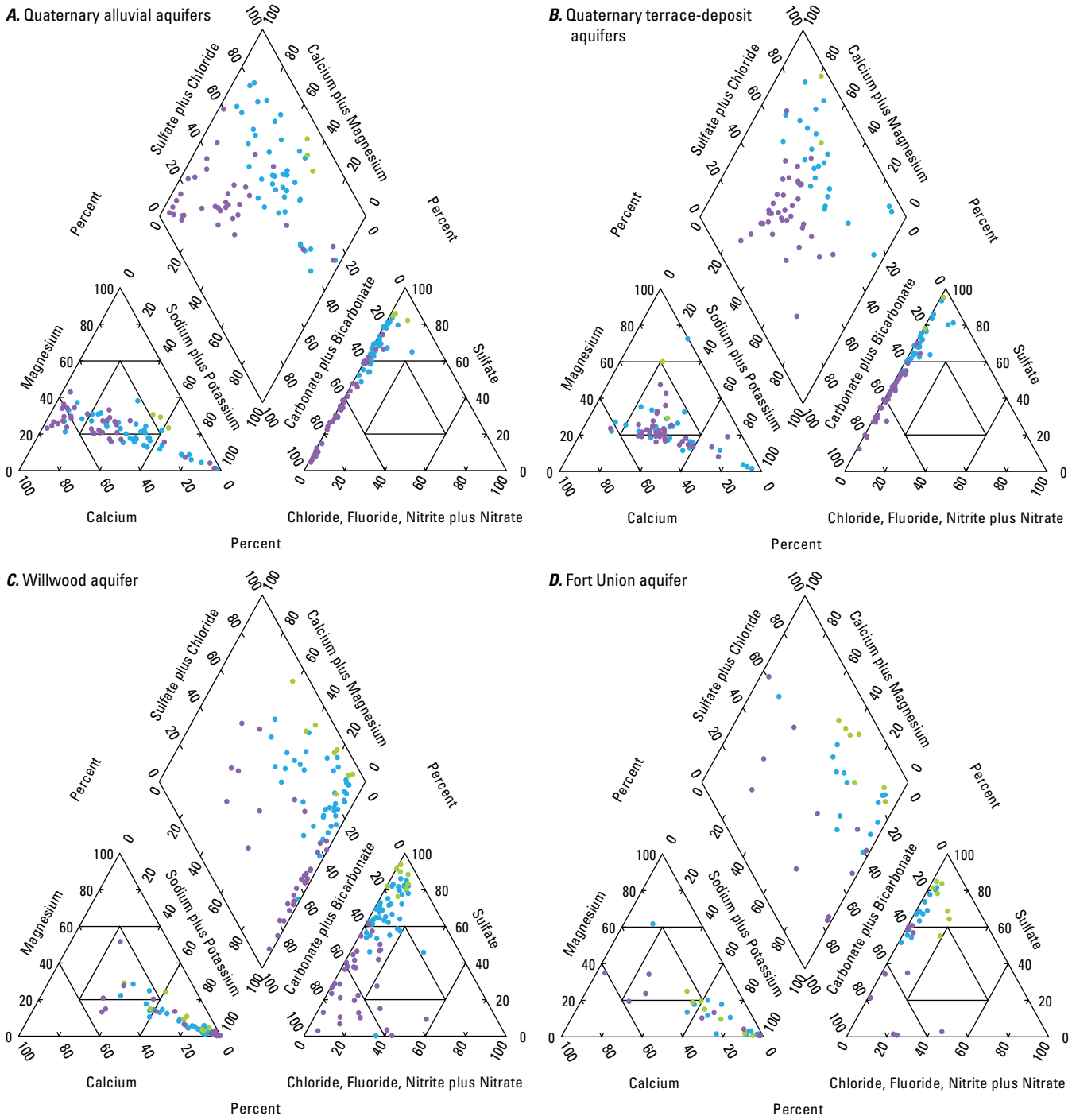
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Wind River Basin, Wyoming.—Continued

Appendix G2-1

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming



EXPLANATION

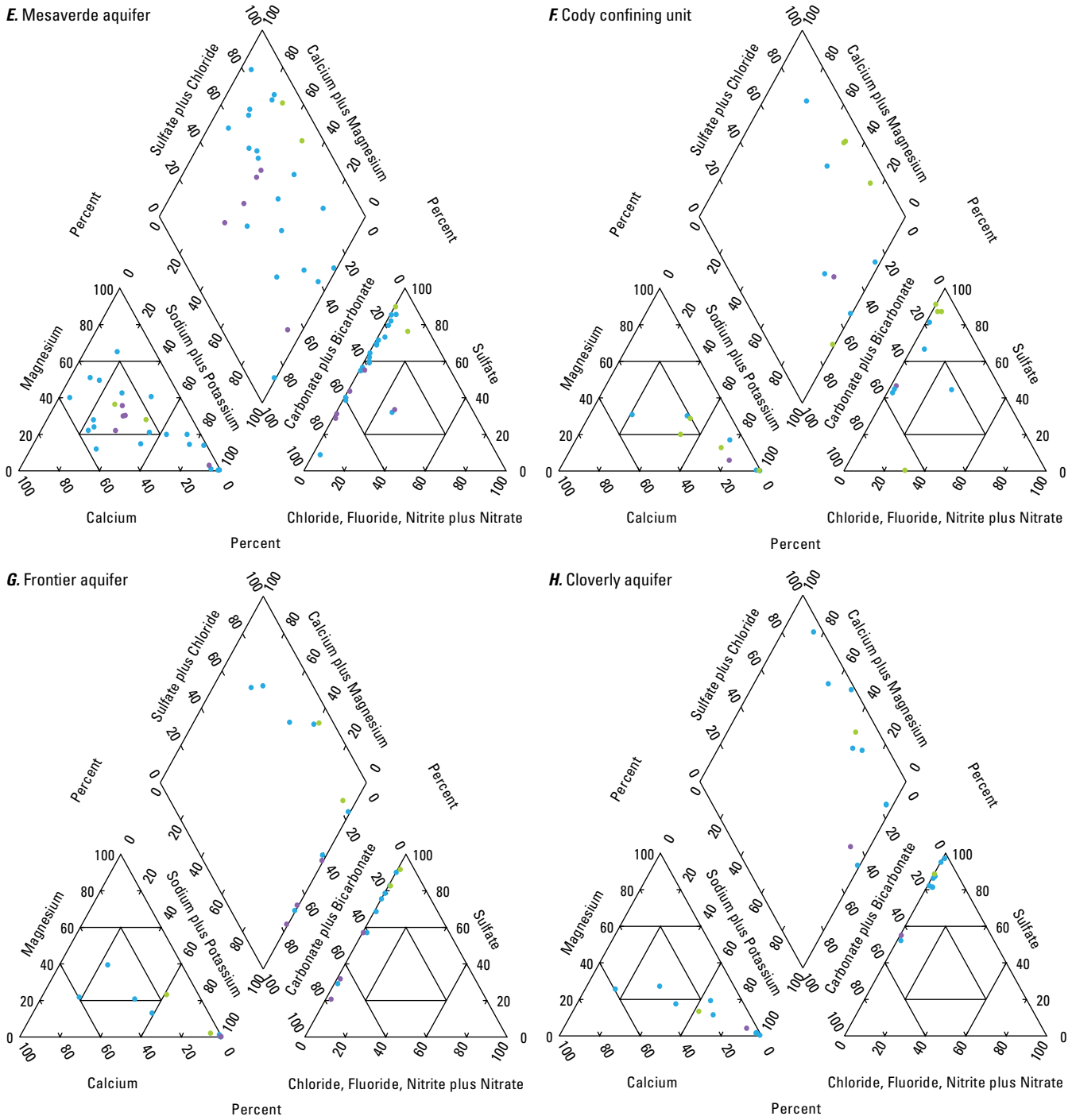
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- 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 G2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming.

Appendix G2-2

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming



EXPLANATION

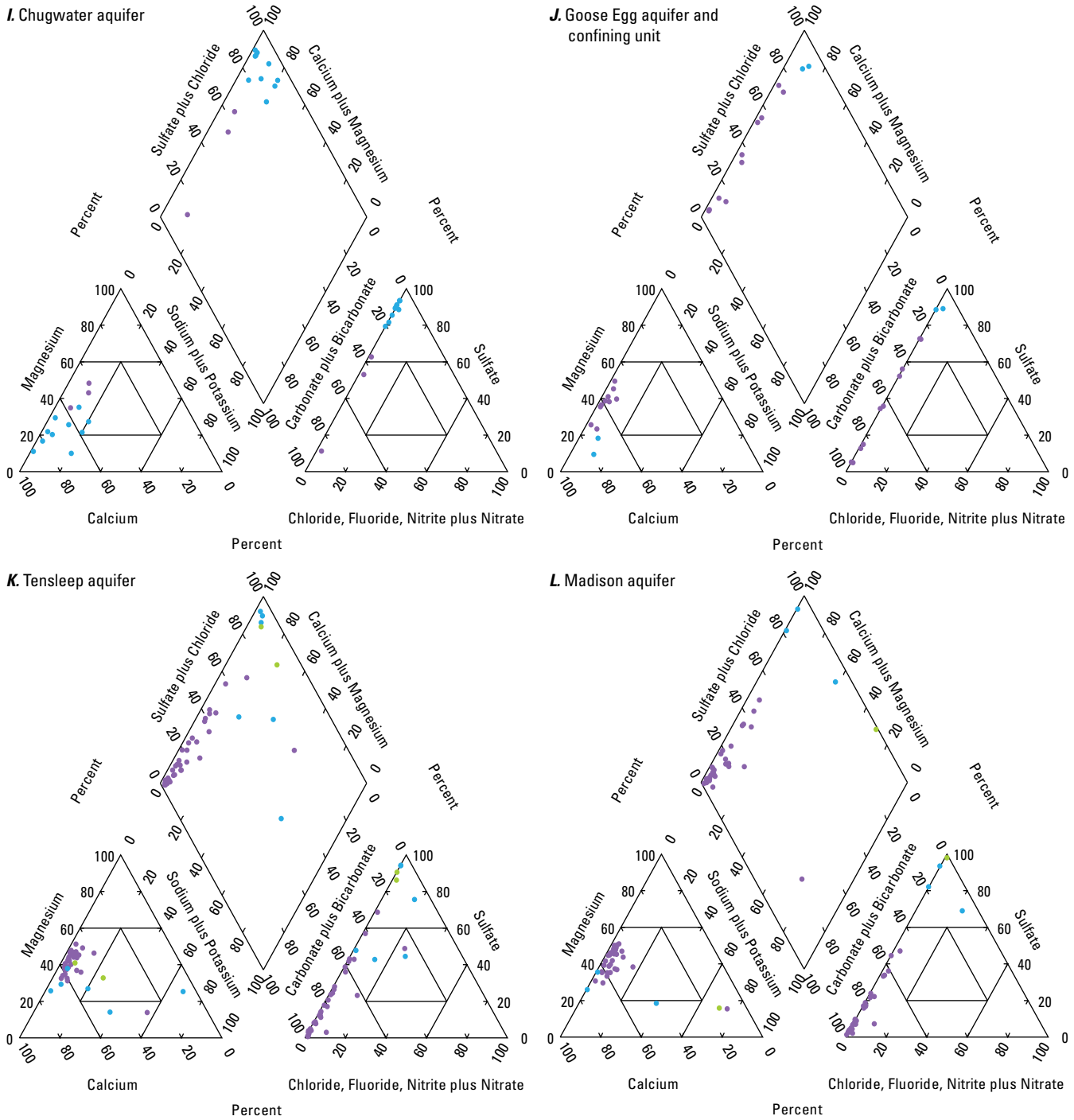
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- 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 G2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming.—Continued

Appendix G2-3

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- Less than or equal to 999; fresh
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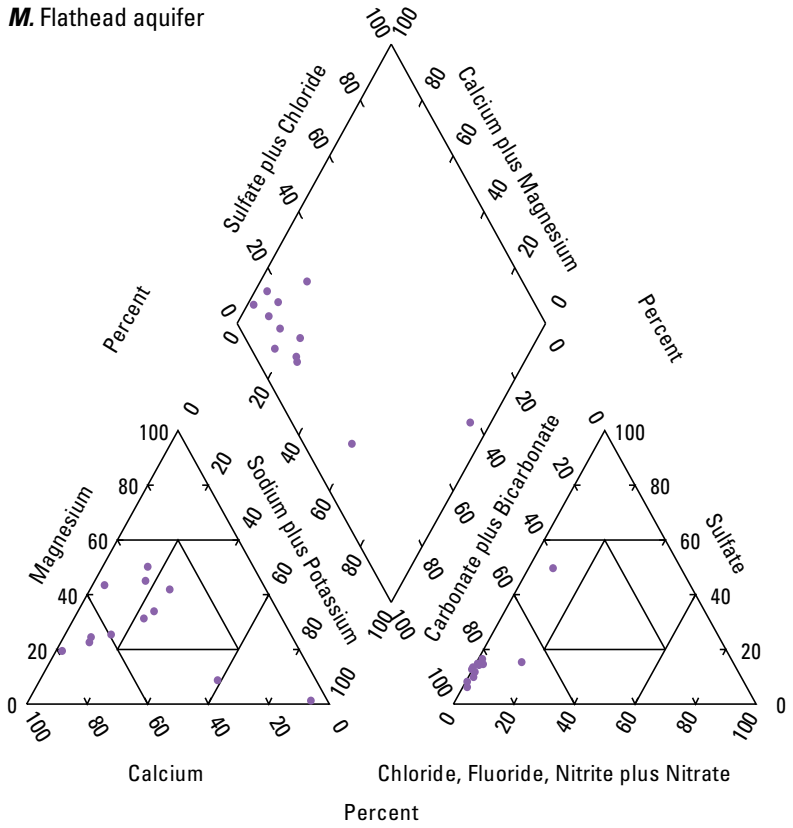
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming.—Continued

Appendix G2-4

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming

M. Flathead aquifer



EXPLANATION

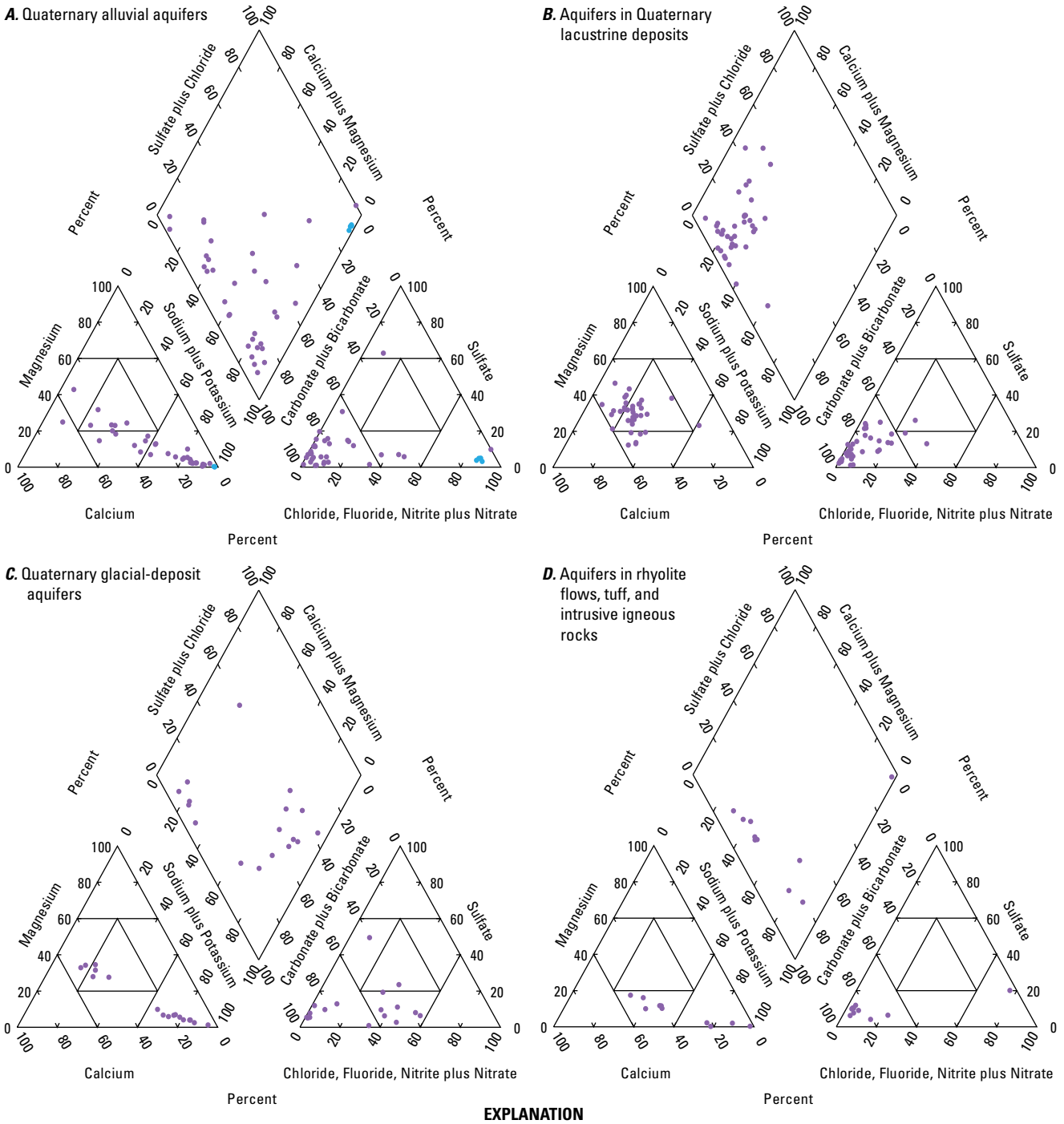
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- 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 G2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Bighorn Basin, Wyoming.—Continued

Appendix G3-1

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming



EXPLANATION

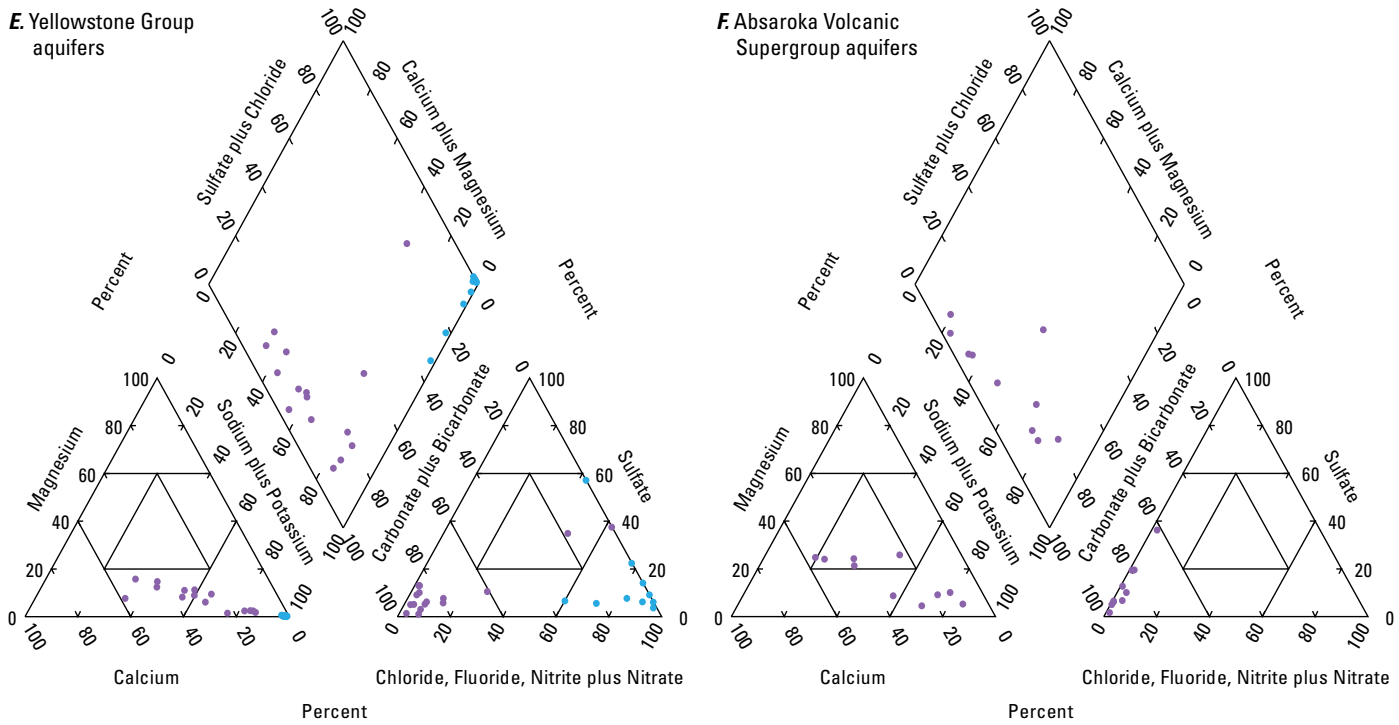
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming.

Appendix G3-2

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

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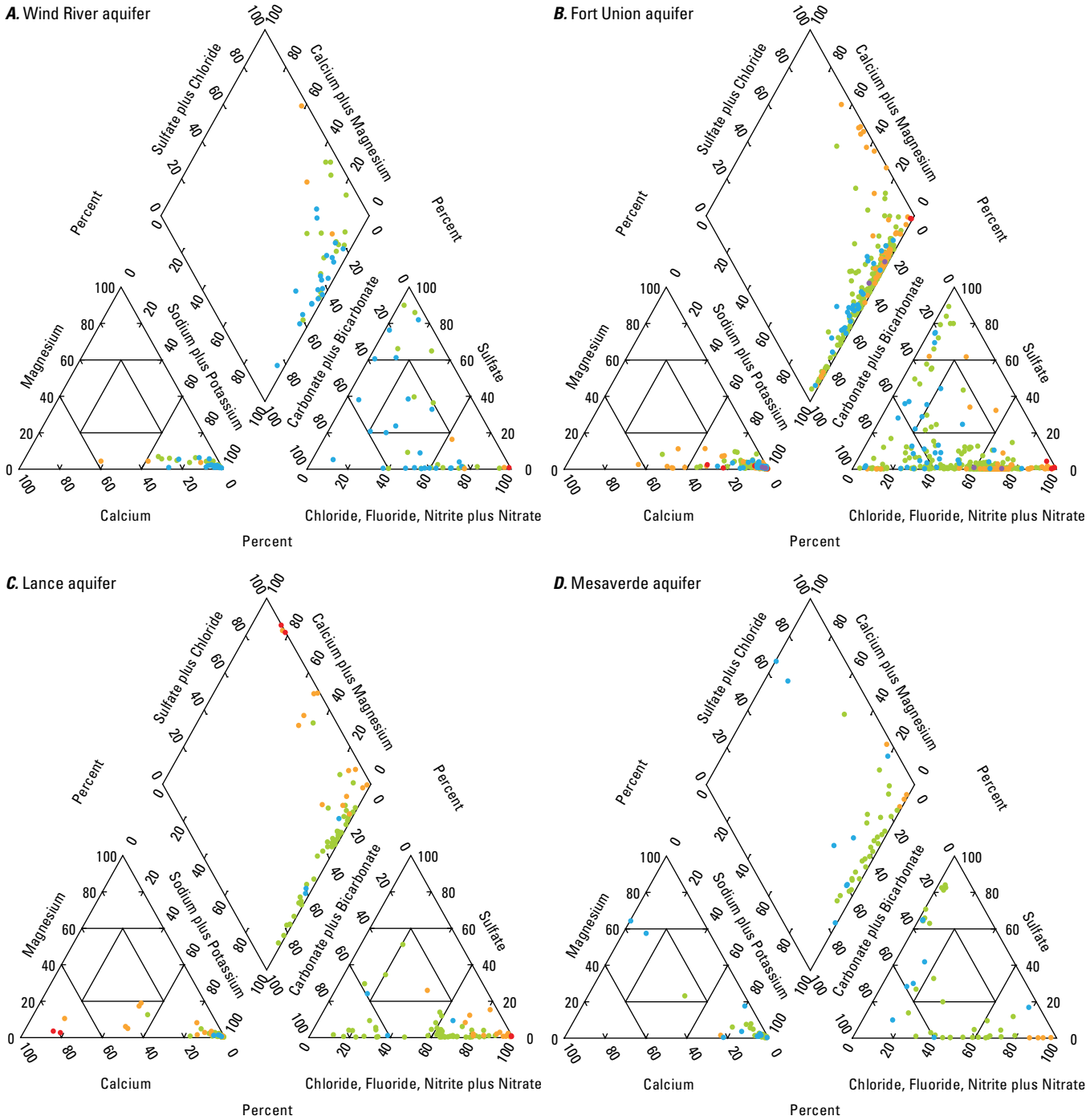
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for environmental groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming.—Continued

Appendix H1-1

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification

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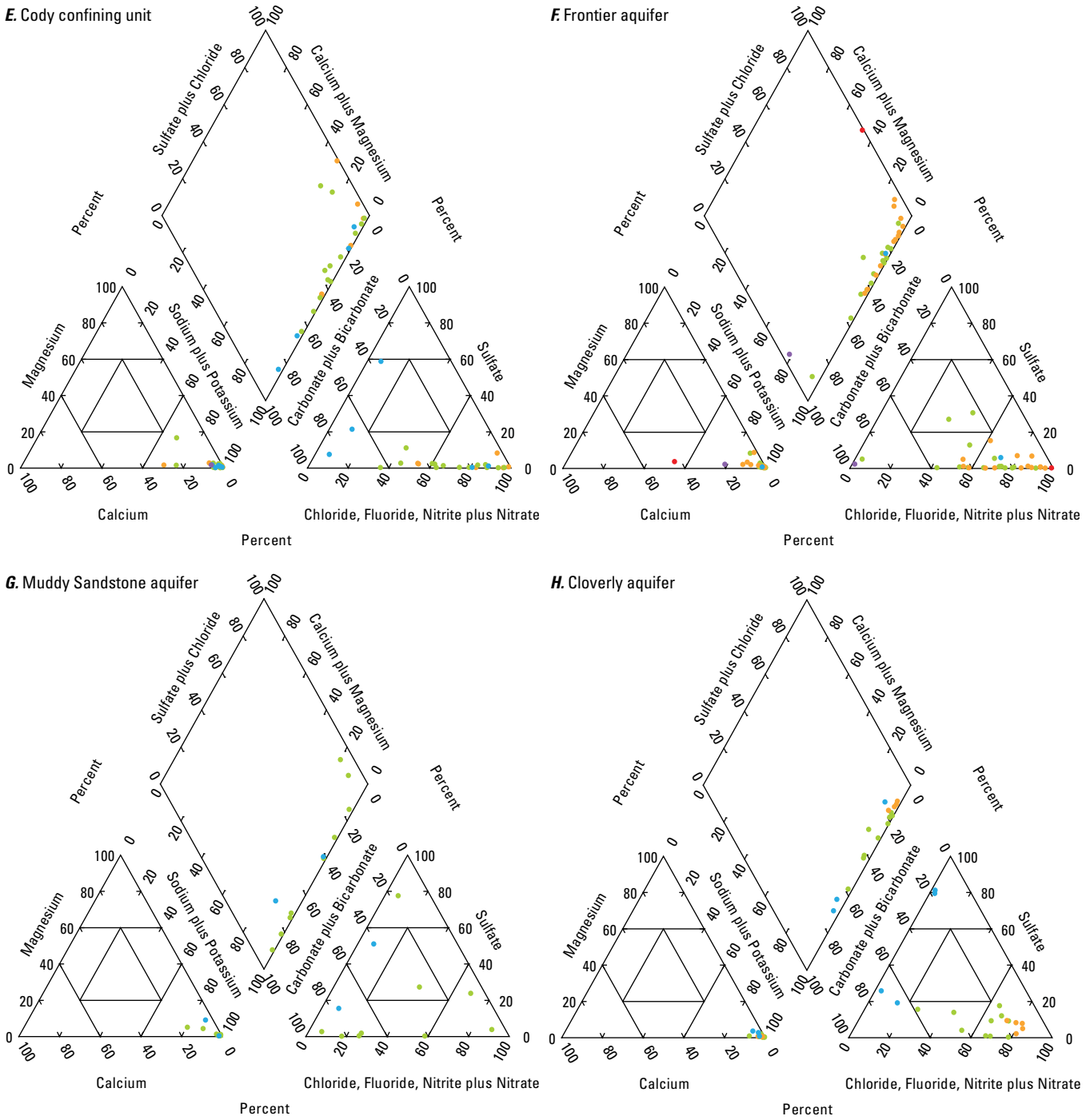
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming.

Appendix H1-2

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming



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- 10,000–34,999; very saline
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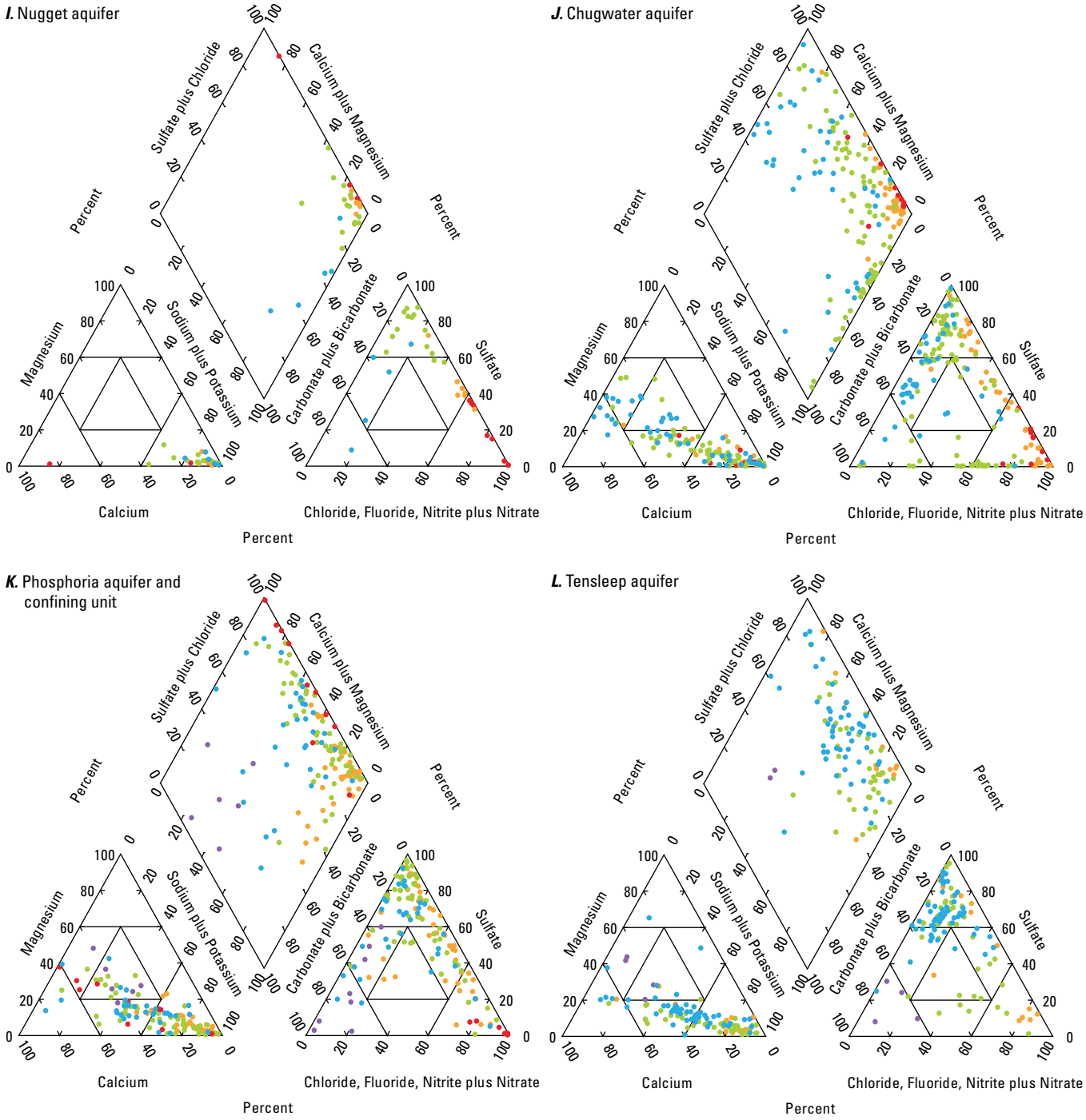
Appendix H1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming.—Continued

Appendix H1-3

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming



EXPLANATION

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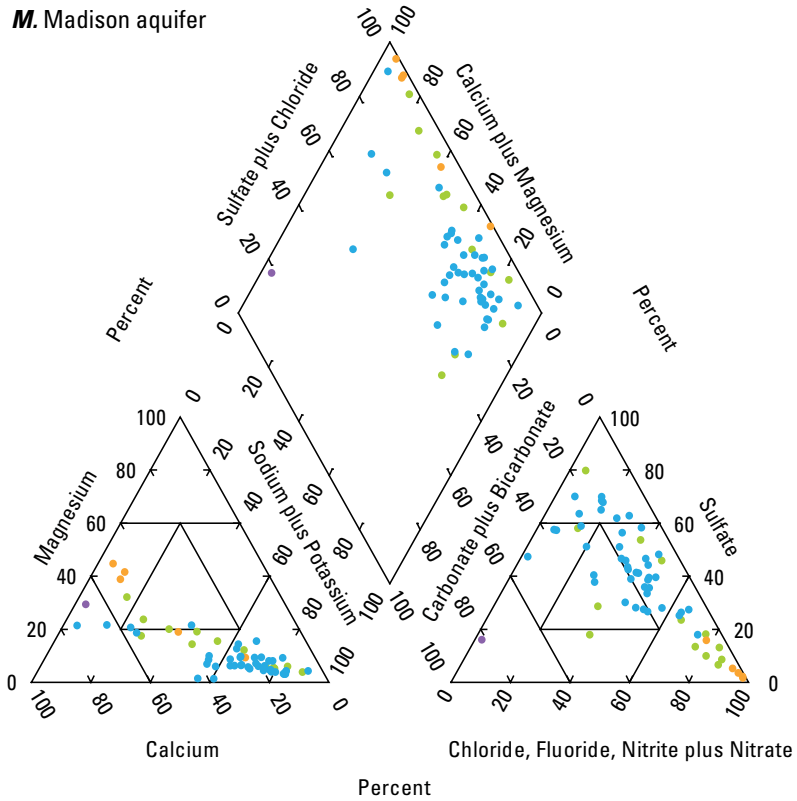
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming.—Continued

Appendix H1-4

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming

M. Madison aquifer



EXPLANATION

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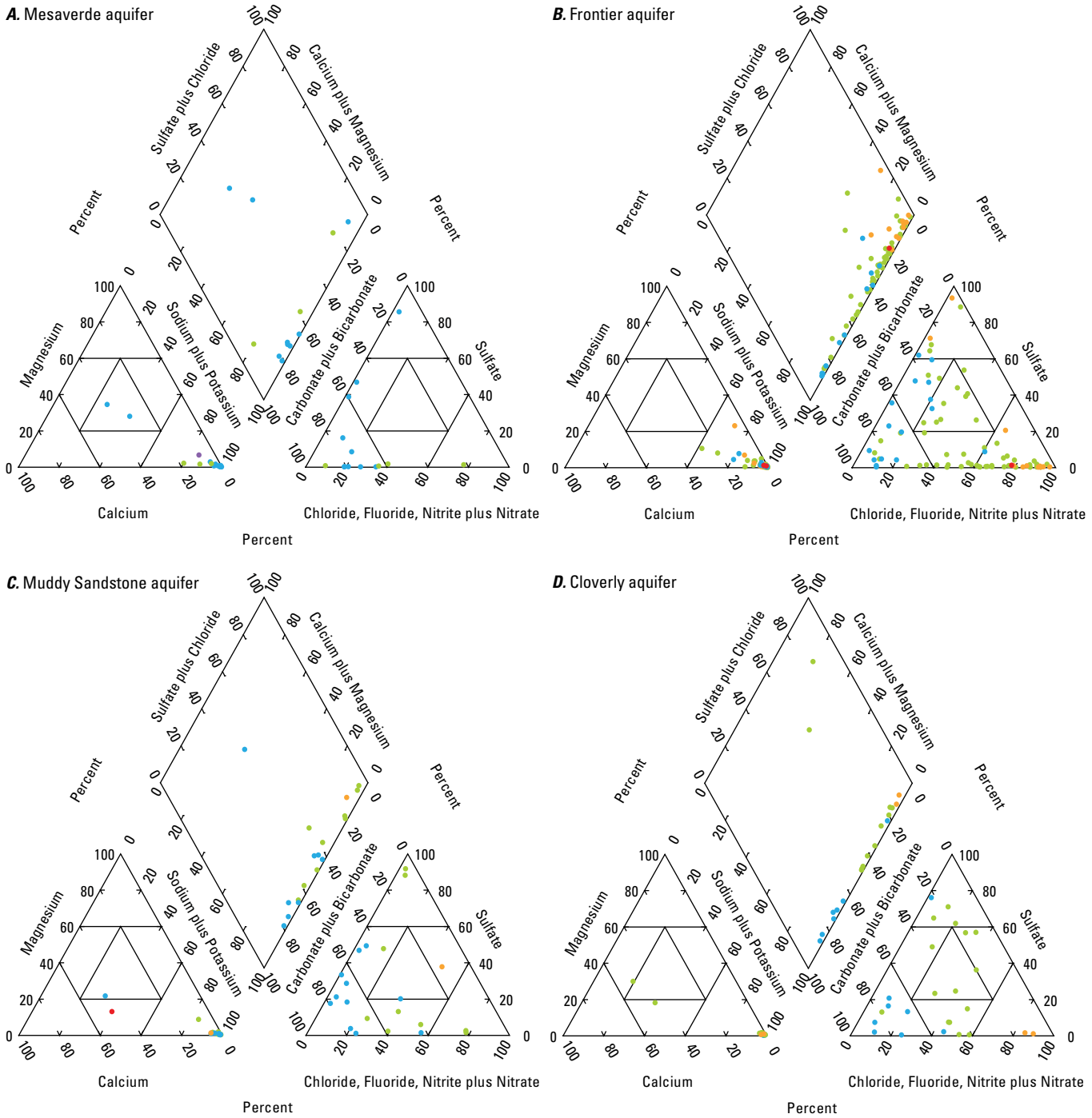
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H1. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Wind River Basin, Wyoming.—Continued

Appendix H2-1

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming



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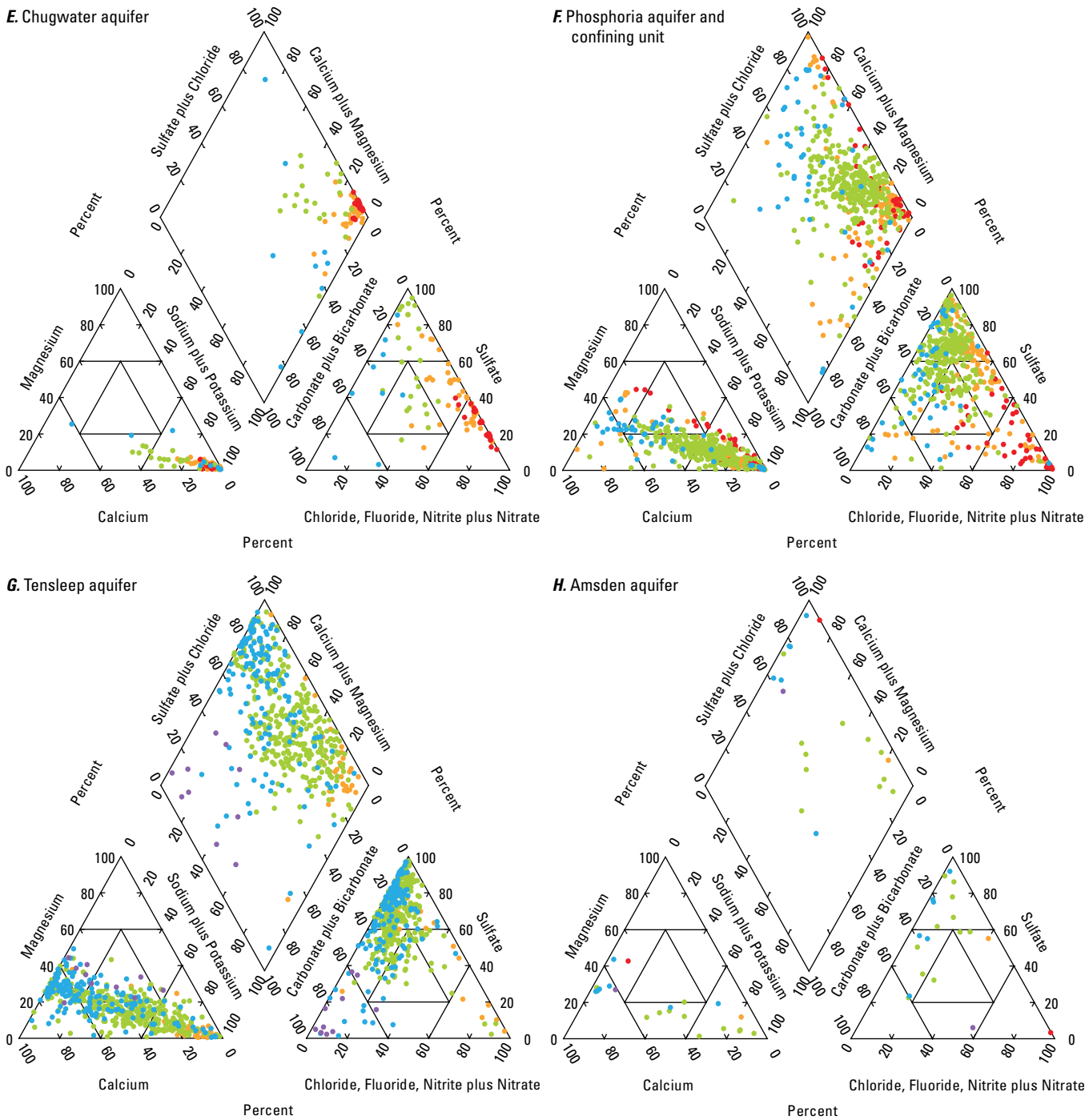
Appendix H2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming.

Appendix H2-2

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming



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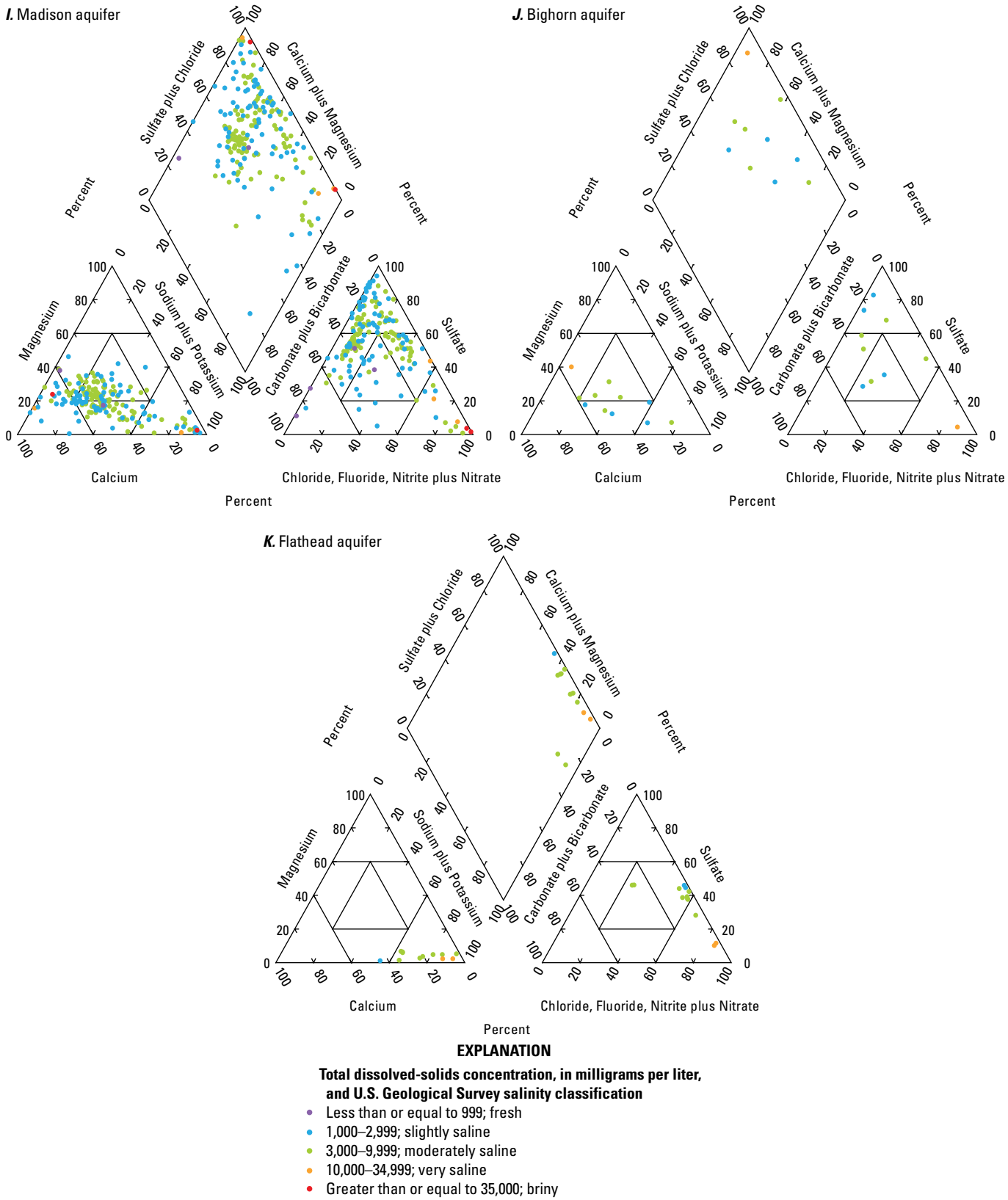
Appendix H2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming.—Continued

Appendix H2-3

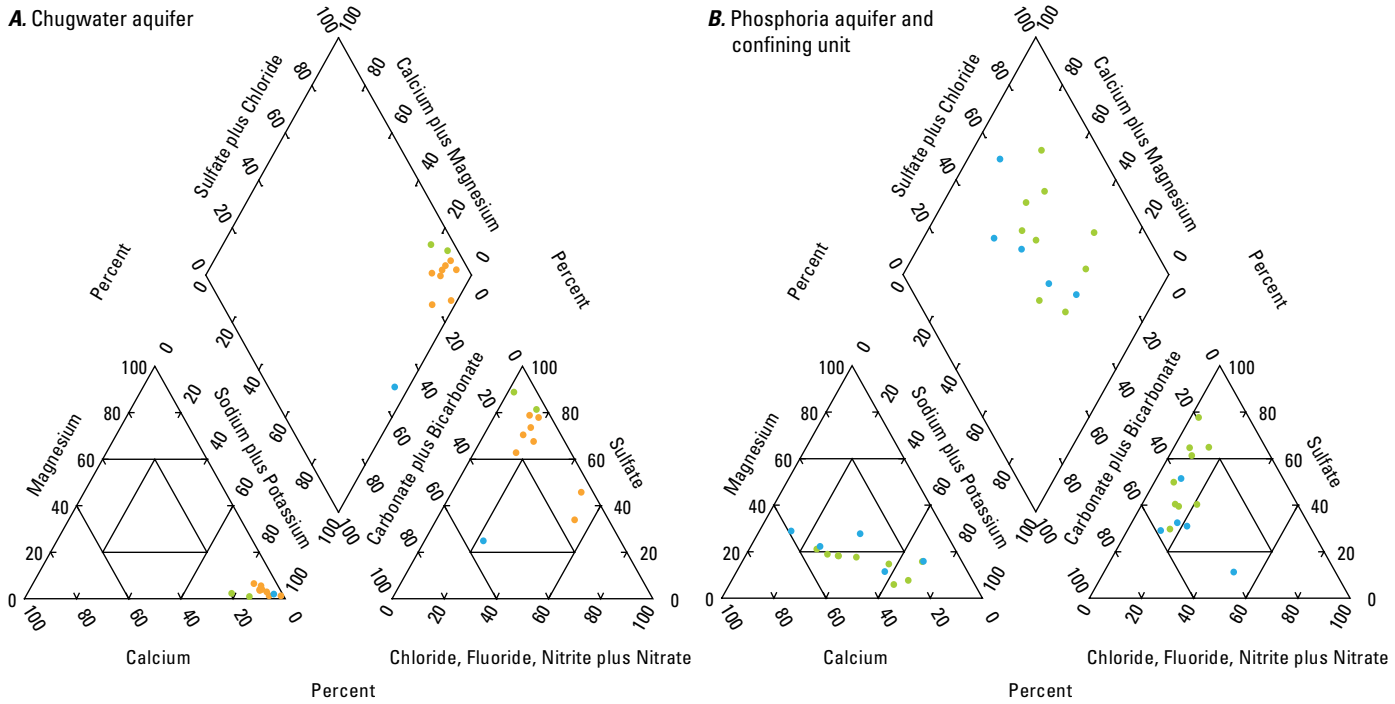
Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming



Appendix H2. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Bighorn Basin, Wyoming.—Continued

Appendix H3

Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming



EXPLANATION

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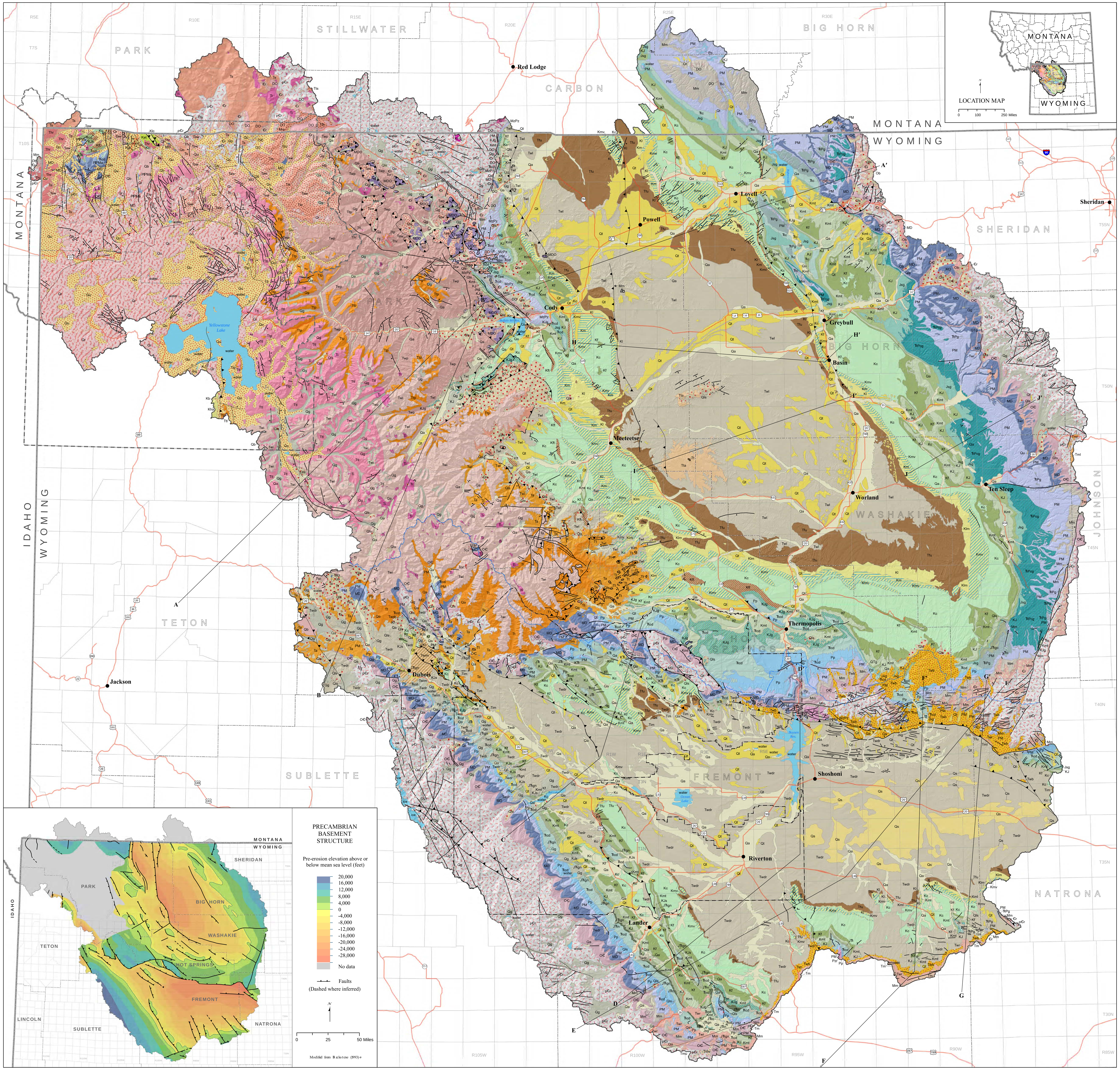
Appendix H3. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for produced groundwater samples from the Absaroka Range and Yellowstone volcanic area, Wyoming.



Surface Geology
Wind/Bighorn River Basin
Wyoming and Montana

compiled
by
Nikolaus Gribb, Brett Worman,
Tomas Gracias, and Scott Quillinan
2012

0 5 10 20 30 Miles

Scale 1:380,000
1 inch equals approximately 6 miles

Explanation

- Interstate highway
- US highway
- State highway
- Wind River/Bighorn River Basin hydrologic divide
- A—A′ Line of section (Plate VI.)
- City or town
- Normal fault - location certain; Normal fault - location concealed } barbell on downthrown side
- State boundary
- County boundary
- Thrust fault - location certain; Thrust fault - location concealed } sawteeth on upper plate
- Township and Range boundaries
- Gravity slide masses related to Heart Mountain, South Fork, and eastern/southeastern Absaroka detachments
- Wind River Indian Reservation boundary
- Yellowstone National Park boundary

Surface Geology

(Units in **boldface** are described in Chapter 7.)

Wyoming Geologic Units

CENOZOIC

Quaternary

Symbol	Unit
Qa	**Alluvium & colluvium**
Qu	Undivided surficial deposits
Ql	**Playa lake and other lacustrine deposits**
Qls	**Landslide deposits**
Qs	**Dune sand and loess deposits**
Qg	**Glacial deposits**
Qt	Gravel, pediment, and fan deposits
QTg	**Terrace gravel deposits**
Qb	**Basalt flows, tuff, and intrusive igneous rocks**
Qr	**Rhyolite flows, tuff, and intrusive igneous rocks**

Upper Tertiary

Symbol	Unit
Thr	Huckleberry Ridge Tuff of Yellowstone Group
Tii	Intrusive and extrusive igneous rocks
Tcv	Caldwell Canyon Volcanics
Tmu	Upper Miocene rocks
Tm	Miocene rocks
Tml	Lower Miocene rocks; includes **Split Rock Formation**

(Qb, Qr and Thr: Yellowstone Group)

Lower Tertiary

Symbol	Unit
Twr	**White River Formation**
Ti	Intrusive igneous rocks
Tts	Thorofare Creek & Sunlight Groups
Twi	Wiggins Formation
Ttl	Two Ocean & Langford Formations
Tt	**Tepee Trail Formation**
Ta	**Aycross Formation**
Ttp	Trout Peak Trachyandesite
Twp	Wapiti Formation
Ts	Crescent Hill Basalt
Taw	Washburn Group
Twb	**Wagon Bed Formation**
Tv	Volcanic conglomerate
Twdr	**Wind River Formation**
Twim	**Wind River & Indian Meadows Formations**
Tta	Tatman Formation
Twl	**Willwood Formation**
Tim	**Indian Meadows Formation**
Tcr	Crandall Conglomerate
Tfu	**Fort Union Formation**
TKu	Sedimentary rocks (undivided)

(Tts through Taw: Absaroka Volcanic Supergroup)

MESOZOIC

Cretaceous

Symbol	Unit
Ki	Intrusive igneous rocks
Kl	**Lance Formation**
Klm	**Lance,** Fox Hills **& Meeteetse Formations &** Bearpaw **& Lewis Shales**
Klc	Landslide Creek Formation
Kha	Harebell Formation
Km	**Meeteetse Formation**
Kml	**Meeteetse Formation & Lewis Shale**
Kle	**Lewis Shale**
Kmv	**Mesaverde Formation**
Kc	**Cody Shale**
Ket	Everts & Telegraph Creek Formations & **Eagle Sandstone**
Kb	Bacon Ridge Sandstone
Kf	**Frontier Formation**
Kft	**Frontier Formation, Mowry Shale, Muddy Sandstone, & Thermopolis Shale**
Kmt	**Mowry Shale, Muddy Sandstone, & Thermopolis Shale**

Cretaceous continued

Symbol	Unit
KJ	**Cloverly & Morrison Formations**
KJs	**Cloverly, Morrison, & Sundance Formations**
KJg	**Cloverly, Morrison, Sundance, & Gypsum Spring Formations**
KJk	Ellis Group
KTR	**Cloverly, Morrison, Sundance, & Gypsum Spring Formations & Nugget Sandstone**

Jurassic

Symbol	Unit
Js	**Sundance Formation**
Jsg	**Sundance & Gypsum Spring Formations**
JTR	**Sundance & Gypsum Spring Formations & Nugget Sandstone**
JTRgn	**Gypsum Spring Formation & Nugget Sandstone**
JTRn	**Nugget Sandstone**
JTRgc	**Gypsum Spring & Chugwater Formations & Nugget Sandstone**

Triassic

Symbol	Unit
TRc	**Chugwater Formation**
TRcd	**Chugwater & Dinwoody Formations**
TRPcg	**Chugwater & Goose Egg Formations**
TRPg	**Goose Egg Formation**
MzPz	Mesozoic & Paleozoic rocks

PALEOZOIC

Symbol	Unit
Pzr	Paleozoic rocks

Permian

Symbol	Unit
Pp	**Phosphoria Formation/Park City Formation**
PIPMa	**Phosphoria & Amsden Formations** & Quadrant Sandstone

Pennsylvanian

Symbol	Unit
PM	**Tensleep Sandstone & Amsden Formation**

Mississippian

Symbol	Unit
Mm	**Madison Limestone**
MD	**Madison Group; Three Forks, & Jefferson Formations**
MO	**Madison Limestone & Bighorn Dolomite**
MDO	**Madison Limestone, Darby, Three Forks, Jefferson** & Beartooth Butte **Formations, Bighorn Dolomite**

Devonian

Symbol	Unit
DO	**Three Forks, Jefferson** & Beartooth Butte **Formations, Bighorn Dolomite**

Ordovician

Symbol	Unit
Ob	**Bighorn Dolomite**
OЄ	**Bighorn Dolomite,** Snowy Range Formation, Pilgrim Limestone, Park & Wolsey Shales, Meagher Limestone, Wolsey Shale & **Flathead Sandstone**

Cambrian

Symbol	Unit
Єr	Cambrian rocks; includes **Gallatin Limestone, Gros Ventre Formation, & Flathead Sandstone**

PRECAMBRIAN

Symbol	Unit
pЄr	**Precambrian rocks**

Montana Geologic Units, as named for their Wyoming equivalents

CENOZOIC

Quaternary

Symbol	Unit
Qa	Alluvium & colluvium
Qu	Undivided surficial deposits
Qg	Glacial deposits
Qt	Gravel, pediment, and fan deposits

Upper Tertiary

Symbol	Unit
Thr	Huckleberry Ridge Tuff of Yellowstone Group
Ti	Intrusive igneous rocks
Tts	Thorofare Creek Group
Twp	Wapiti Formation
Ts	Crescent Hill Basalt
Taw	Washburn Group
Twl	Willwood Formation
Tfu	Fort Union Formation

MESOZOIC

Cretaceous

Symbol	Unit
Kl	Lance Formation
Km	Meeteetse Formation
Kmv	Mesaverde Formation
Kc	Cody Shale
Kf	Frontier Formation
Kft	Frontier Formation, Mowry & Thermopolis Shales
Kmt	Mowry Shale, Muddy Sandstone, & Thermopolis Shale
KJ	Cloverly & Morrison Formations
KJg	Cloverly, Morrison, Sundance, & Gypsum Spring Formations

Jurassic

Symbol	Unit
Jsg	Sundance & Gypsum Spring Formations, Nugget Sandstone

Triassic

Symbol	Unit
TRc	Chugwater Formation
TRPg	Goose Egg Formation
MzPz	Mesozoic & Paleozoic rocks

PALEOZOIC

Permian

Symbol	Unit
Pp	Phosphoria Formation

Pennsylvanian

Symbol	Unit
PM	Tensleep & Amsden Formations

Mississippian

Symbol	Unit
Mm	Madison Limestone
MD	Madison Group, Three Forks, & Jefferson Formations

Devonian

Symbol	Unit
DO	Three Forks, Jefferson, & Beartooth Butte Formations & Bighorn Dolomite

Ordovician

Symbol	Unit
Ob	Bighorn Dolomite
OЄ	Ordovician & Cambrian (undivided)

Cambrian

Symbol	Unit
Єr	Cambrian rocks (undivided)

PRECAMBRIAN

Symbol	Unit
pЄr	Precambrian rocks

Disclaimer

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Modified from Blackstone (1993)

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ERA	System and Series		Lithostratigraphic units of Love et al. (1993): Wind River Range	Lithostratigraphic units of Love et al. (1993): Wind River Basin	Hydrogeologic role/unit of Richter (1981)	Hydrogeologic unit of Wyoming Statewide Framework Plan (WWC Engineering et al., 2007, fig. 4-9)	Hydrogeologic unit used in this report	
CENOZOIC	Quaternary	Holocene and Pleistocene	Alluvium, terrace deposits, landslide deposits, dune sand (eolian) deposits, and glacial deposits		Major aquifer	Major aquifer–alluvial	Alluvial aquifers, terrace-deposit aquifers, aquifers in landslide deposits, aquifers in dune sand (eolian) deposits, and glacial-deposit aquifers	Quaternary unconsolidated-deposit aquifers
CENOZOIC	Tertiary	Pliocene[1]						
CENOZOIC	Tertiary	Miocene	South Pass Formation[2]; Split Rock Formation[3]	Split Rock Formation[3]	Aquifer (Arikaree aquifer)[3]	Major aquifer–sandstone	Split Rock aquifer	
CENOZOIC	Tertiary	Oligocene	White River Formation			Marginal aquifer	White River aquifer	
CENOZOIC	Tertiary	Eocene	Upper and middle Eocene rocks[2]; Eocene rocks[2]; Tepee Trail Fm; Aycross Fm; Wagon Bed Fm		Leaky confining unit	Wagon Bed Formation–marginal aquifer	Aycross–Wagon Bed confining unit	
CENOZOIC	Tertiary	Eocene	Wind River Formation		Major aquifer (Wind River aquifer)	Major aquifer–sandstone	Wind River aquifer	
CENOZOIC	Tertiary	Eocene	Conglomerate of Roaring Fork[2]	Indian Meadows Fm	Leaky confining unit	Major aquitard	Indian Meadows confining unit	
CENOZOIC	Tertiary	Paleocene		Fort Union Fm; Shotgun Mbr; Waltman Shale Mbr; Lower unnamed Mbr	Aquifer (Fort Union–Lance aquifer)	Minor aquifer	Fort Union aquifer	Fort Union–Lance aquifer
MESOZOIC	Cretaceous	Upper Cretaceous		Lance Formation		Major aquifer–sandstone	Lance aquifer	
MESOZOIC	Cretaceous	Upper Cretaceous		Meeteetse Fm; Lewis Shale; Lewis Shale	Confining unit	Major aquitard	Meeteetse–Lewis confining unit	
MESOZOIC	Cretaceous	Upper Cretaceous	Mesaverde Formation	Mesaverde Formation: Teapot Sandstone Member	Confined subaquifer (Teapot horizon aquifer); Aquifer (Measaverde aquifer)	Minor aquifer	Teapot Sandstone aquifer	Mesaverde aquifer
MESOZOIC	Cretaceous	Upper Cretaceous		Mesaverde Formation: Middle unnamed member	Confining unit; Aquifer (Measaverde aquifer)		Middle confining unit	
MESOZOIC	Cretaceous	Upper Cretaceous		Mesaverde Formation: Parkman Ss Mbr	Confined subaquifer (Parkman-Fales aquifer); Aquifer (Measaverde aquifer)		Parkman Ss aquifer	
MESOZOIC	Cretaceous	Upper Cretaceous		Mesaverde Formation: Wallace Creek Tongue of Cody Shale	Confined subaquifer (Parkman-Fales aquifer); Aquifer (Measaverde aquifer)		Confining unit	
MESOZOIC	Cretaceous	Upper Cretaceous		Mesaverde Formation: Fales Ss Member	Confined subaquifer (Parkman-Fales aquifer); Aquifer (Measaverde aquifer)		Fales Ss aquifer	
MESOZOIC	Cretaceous	Upper Cretaceous	Cody Shale	Cody Shale	Regional confining unit	Major aquitard	Cody confining unit	
MESOZOIC	Cretaceous	Upper Cretaceous	Frontier Formation		Aquifer (Frontier aquifer); Regional confining unit	Minor aquifer	Frontier aquifer; Basal regional confining unit	Lower and middle Mesozoic aquifers and confining units
MESOZOIC	Cretaceous	Upper Cretaceous	Mowry Shale		Leaky confining unit/regional confining unit	Major aquitard	Mowry confining unit	Mowry–Thermopolis confining unit
MESOZOIC	Cretaceous	Lower Cretaceous	Muddy Sandstone		Aquifer (Muddy aquifer)	? Muddy Sandstone[4] ?	Muddy Sandstone aquifer	Mowry–Thermopolis confining unit
MESOZOIC	Cretaceous	Lower Cretaceous	Thermopolis Shale		Leaky confining unit/regional confining unit	Major aquitard	Thermopolis confining unit	Mowry–Thermopolis confining unit
MESOZOIC	Cretaceous	Lower Cretaceous	"Dakota Sandstone"; "Fuson Shale"; "Lakota Sandstone"; Cloverly Formation		Aquifer (Cloverly aquifer)	Minor aquifer	Cloverly aquifer	
MESOZOIC	Jurassic	Upper Jurassic	Morrison Formation		Leaky confining unit	Minor aquifer	Morrison confining unit	
MESOZOIC	Jurassic	Middle Jurassic	Sundance Formation		Regional aquifer (Sundance–Nugget aquifer)	Minor aquifer	Sundance aquifer	Sundance–Nugget aquifer
MESOZOIC	Jurassic	Middle Jurassic	Gypsum Spring Formation		Regional confining unit/leaky confining unit	Marginal aquifer	Gypsum Spring confining unit	Sundance–Nugget aquifer
MESOZOIC	Jurassic(?) and Triassic(?)		Nugget Sandstone		Not discussed	Major aquifer–Sandstone	Nugget aquifer	Sundance–Nugget aquifer
MESOZOIC	Triassic	Upper Triassic	Chugwater Group or Fm: Popo Agie Formation or Member		Confining unit; Leaky confining unit	Marginal aquifer	Chugwater–Dinwoody aquifer and confining unit: Popo Agie confining unit	
MESOZOIC	Triassic	Upper Triassic	Chugwater Group or Fm: Crow Mountain Ss or Sandstone Member		Aquifer; Leaky confining unit	Marginal aquifer	Chugwater aquifer: Crow Mountain aquifer	
MESOZOIC	Triassic	Lower Triassic	Chugwater Group or Fm: Alcova Limestone or Limestone Member		Confining unit; Leaky confining unit	Marginal aquifer	Chugwater aquifer: Alcova confining unit	
MESOZOIC	Triassic	Lower Triassic	Chugwater Group or Fm: Red Peak Formation or Member		Aquifer; Leaky confining unit	Marginal aquifer	Chugwater aquifer: Red Peak aquifer	
MESOZOIC	Triassic	Lower Triassic	Dinwoody Formation	Goose Egg Formation	Confining unit	Marginal aquifer	Dinwoody c.u.	Goose Egg aquifer and confining unit
PALEOZOIC	Permian		Phosphoria Formation and related rocks (Park City Fm)	Goose Egg Formation	Aquifer/leaky confining unit (Phosphoria aquifer)	Minor aquifer	Phosphoria aquifer and confining unit	Goose Egg–Phosphoria aquifer and confining unit
PALEOZOIC	Pennsylvanian	Upper Pennsylvanian; Middle Pennsylvanian	Tensleep Sandstone		Aquifer (Tensleep subaquifer); Tensleep aquifer system	Major aquifer–limestone[5]	Tensleep aquifer	Paleozoic aquifer system
PALEOZOIC	Pennsylvanian	Lower Pennsylvanian	Amsden Formation		Aquifer (Amsden subaquifer); Tensleep aquifer system	Marginal aquifer	Amsden aquifer	Paleozoic aquifer system
PALEOZOIC	Mississippian	Upper Mississippian	Darwin Ss Mbr		Aquifer (Amsden subaquifer); Tensleep aquifer system			Paleozoic aquifer system
PALEOZOIC	Mississippian	Lower Mississippian	Madison Limestone		Aquifer (Madison subaquifer); Tensleep aquifer system	Major aquifer–limestone	Madison aquifer	Paleozoic aquifer system
PALEOZOIC	Devonian	Upper Devonian	Darby Formation		Aquifer (Darby subaquifer); Tensleep aquifer system	Major aquifer–limestone	Darby aquifer	Paleozoic aquifer system
PALEOZOIC	Silurian[6]				Aquifer (Darby subaquifer); Tensleep aquifer system			Paleozoic aquifer system
PALEOZOIC	Ordovician	Upper Ordovician; Middle Ordovician	Bighorn Dolomite[7]		Aquifer (Bighorn subaquifer); Tensleep aquifer system	Major aquifer–limestone/ minor aquifer	Bighorn aquifer	Paleozoic aquifer system
PALEOZOIC	Cambrian	Upper Cambrian	Snowy Range Formation[2]; Pilgrim Limestone[2]	Gallatin Limestone	Leaky confining unit	Minor aquifer	Gallatin confining unit	Gallatin–Gros Ventre confining unit
PALEOZOIC	Cambrian	Middle Cambrian	Gros Ventre Formation		Leaky confining unit	Minor aquifer	Gros Ventre confining unit	Gallatin–Gros Ventre confining unit
PALEOZOIC	Cambrian		Flathead Sandstone		Aquifer (Flathead aquifer)	Major aquifer–limestone[5]	Flathead aquifer	
Precambrian			Precambrian rocks			Major aquitard	Precambrian basal confining unit	

[1]Pliocene rocks not present in Wind River Basin.

[2]Function of lithostratigraphic unit as hydrogeologic unit not defined.

[3]Split Rock Formation previously defined as Arikaree Formation in Wind River Basin (Love et al., 1993).

[4]Function of Muddy Sandstone as hydrogeologic unit not defined in WWC Engineering et al. (2007, fig. 4-9).

[5]Predominant lithology of formation is sandstone, and it is unknown why formation is defined as "Major aquifer–limestone" in WWC Engineering et al. (2007, fig. 4-9).

[6]Silurian rocks not present in Wind River Basin.

[7]Composed of upper Leigh Dolomite Member and Lander Sandstone Member (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein).

Abbreviations used in the columns:

c.u. Confining unit
Fm Formation
Ss Sandstone
Mbr Member

Modified from Richter (1981); Love et al. (1993); and WWC Engineering et al. (2007)

Plate II. Relation of lithostratigraphic units to hydrogeologic units, Wind River Basin, Wyoming.

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ERA	System and Series		Lithostratigraphic units of Love et al. (1993) in Bighorn Basin and Owl Creek and Bighorn Mountains	Hydrogeologic division of Lowry et al. (1976)	Hydrogeologic unit of Libra et al. (1981)	Hydrogeologic unit of Western Water Consultants, Inc. (1982a,b) and Doremus (1986)	Hydrogeologic unit of Western Water Consultants, Inc. (1983b)	Hydrogeologic unit of Cooley (1984, 1986)	Hydrogeologic unit of Jarvis (1986a) and Spencer (1986a)	Hydrogeologic unit of Wyoming Statewide Framework Plan (WWC Engineering et al., 2007, fig. 4-9)	Hydrogeologic unit used in this report
CENOZOIC	Quaternary	Holocene and Pleistocene	Quaternary alluvium, terrace deposits, and glacial deposits	1	Major aquifer	Principal aquifers	Secondary aquifer	Not discussed	Not discussed	Major aquifer	Alluvial aquifers, terrace-deposit aquifers, and glacial-deposit aquifers; Quaternary unconsolidated-deposit aquifers
CENOZOIC	Tertiary	Pliocene[1]			Upper Cretaceous/Tertiary aquifer system	Units not present and (or) discussed in study					
CENOZOIC	Tertiary	Miocene	Lower Miocene and Oligocene rocks[2]								
CENOZOIC	Tertiary	Oligocene	White River Formation	2						Marginal aquifer	White River aquifer
CENOZOIC	Tertiary	Eocene	Wapiti Formation[2]; Aycross Formation[2]; Wagon Bed Formation							Wagon Bed Formation–marginal aquifer	Wagon Bed confining unit
CENOZOIC	Tertiary	Eocene	Tatman Formation[2]								
CENOZOIC	Tertiary	Eocene	Willwood Formation		Aquifer/discontinuous aquifers and confining units		Secondary aquifer			Minor aquifer	Willwood aquifer[7]
CENOZOIC	Tertiary	Paleocene	Fort Union Formation		Aquifer/discontinuous aquifers and confining units		Secondary aquifer			Major aquifer–sandstone	Fort Union aquifer; Lower Tertiary/Upper Cretaceous aquifer system
MESOZOIC	Cretaceous	Upper Cretaceous	Lance Formation	3	Aquifer/discontinuous aquifers and confining units	Principal aquifer (Lance–Meeteetse–Mesaverde aquifer)	Secondary aquifer			Major aquifer	Lance aquifer
MESOZOIC	Cretaceous	Upper Cretaceous	Meeteetse Formation; Lewis Shale		Aquifer/discontinuous aquifers and confining units		Secondary aquifer			Major aquitard	Meeteetse aquifer and confining unit
MESOZOIC	Cretaceous	Upper Cretaceous	Mesaverde Formation; Teapot Sandstone Member; Eagle Sandstone		Aquifer/discontinuous aquifers and confining units		Secondary aquifer			Major aquifer–sandstone	Mesaverde aquifer
MESOZOIC	Cretaceous	Upper Cretaceous	Cody Shale	4	Regional aquitard	Major regional confining unit	Leaky confining unit			Major aquitard	Cody confining unit
MESOZOIC	Cretaceous	Upper Cretaceous	Frontier Formation		Minor aquifer	Principal aquifer (Frontier aquifer)	Alternating leaky confining units and secondary aquifers			Minor aquifer	Frontier aquifer[7]
MESOZOIC	Cretaceous	Upper Cretaceous	Mowry Shale		Aquitard	Leaky confining unit; Regional confining unit	Leaky confining unit			Major aquitard	Mowry confining unit; Mowry-Thermopolis c.u.
MESOZOIC	Cretaceous	Lower Cretaceous	Muddy Sandstone		Aquitard	Minor aquifer	Secondary aquifer			? Muddy Sandstone ?[4]	Muddy Ss aquifer
MESOZOIC	Cretaceous	Lower Cretaceous	Thermopolis Shale			Leaky confining unit	Leaky confining unit			Major aquitard	Thermopolis confining unit
MESOZOIC	Cretaceous	Lower Cretaceous	"Dakota Sandstone"; Cloverly Formation; "Lakota Sandstone"		Minor aquifer	Principal aquifer (Cloverly aquifer)	Secondary aquifer			Major aquifer–sandstone	Cloverly aquifer[7]; Lower and middle Mesozoic aquifers and confining units
MESOZOIC	Cretaceous	Lower Cretaceous	Morrison Formation		Minor aquifer and (or) local confining unit	Major regional confining unit	Alternating leaky confining units and secondary aquifers			Minor aquifer	Morrison confining unit and aquifer[7]
MESOZOIC	Jurassic	Upper Jurassic	Sundance Formation	5	Minor aquifer and (or) local confining unit		Alternating leaky confining units and secondary aquifers			Marginal aquifer	Sundance confining unit and aquifer
MESOZOIC	Jurassic	Middle Jurassic	Gypsum Spring Formation		Minor aquifer and (or) local confining unit	Major regional confining unit	Alternating leaky confining units and secondary aquifers			Marginal aquifer	Gypsum Spring confining unit and aquifer
MESOZOIC	Jurassic(?) and Triassic(?)		Nugget Sandstone		? Nugget[2] ?		Leaky confining unit			Major aquifer–sandstone	Nugget aquifer
MESOZOIC	Triassic	Upper Triassic	Chugwater Group or Formation: Popo Agie Formation or Member; Crow Mountain Sandstone or Sandstone Member; Alcova Limestone or Limestone Member		Minor aquifer and (or) local confining unit			Confining unit	Leaky confining unit	Marginal aquifer	Chugwater–Dinwoody aquifer and confining unit; Chugwater aquifer[7]
MESOZOIC	Triassic	Lower Triassic	Chugwater Group or Formation: Red Peak Formation or Member								
MESOZOIC	Triassic	Lower Triassic	Dinwoody Formation; Goose Egg Formation		Minor aquifer and (or) local confining unit	Dinwoody Formation–leaky confining unit; Principal aquifer (Phosphoria–Tensleep aquifer)	Dinwoody Formation–leaky confining unit; Secondary aquifer	Minor aquifer and discontinuous confining unit	Dinwoody Formation–leaky confining unit; Aquifer (Park City[3]–Tensleep aquifer)	Dinwoody Formation–marginal aquifer; Minor aquifer; Marginal aquifer	Dinwoody confining unit; Phosphoria aquifer and confining unit[7]; Goose Egg aquifer and confining unit; Goose Egg–Phosphoria aquifer and confining unit; Paleozoic aquifer system
PALEOZOIC	Permian		Phosphoria Formation and related rocks (Park City Fm); Possible uppermost Minnelusa Formation[2]								
PALEOZOIC	Pennsylvanian	Upper Pennsylvanian	Tensleep Sandstone	6	Major aquifer	Principal aquifer	Principal aquifer	Major aquifer		Major aquifer–limestone[5]	Tensleep aquifer[7]
PALEOZOIC	Pennsylvanian	Middle Pennsylvanian	Amsden Formation: Ranchester Limestone Member		Minor aquifer	Major regional confining unit	Leaky confining unit	Upper Amsden Fm–confining unit	Ranchester Limestone Member of Amsden Formation	Marginal aquifer	Amsden confining unit[7]
PALEOZOIC	Pennsylvanian	Lower Pennsylvanian	Amsden Formation: Horseshoe Shale Member					Darwin Sandstone Member of Amsden Formation	Horseshoe Shale Member of Amsden Fm (Amsden confining unit)		
PALEOZOIC	Mississippian	Upper Mississippian	Darwin Ss Mbr		Darwin Ss Mbr–Minor aquifer				Darwin Ss Mbr of Amsden Fm		Madison aquifer[7]; Madison–Bighorn aquifer
PALEOZOIC	Mississippian	Lower Mississippian	Madison Limestone		Major aquifer	Principal aquifer (Madison aquifer)	Principal aquifer	Major aquifer (Madison–Bighorn aquifer)	Aquifer (Madison aquifer)	Major aquifer–limestone	
PALEOZOIC	Devonian	Upper Devonian	Darby Formation; Three Forks Formation; Jefferson Formation		Three Forks and Jefferson Formations–aquitard/local confining unit and (or) minor aquifer		Jefferson Formation–Leaky confining unit			Major aquifer–limestone	Darby aquifer
PALEOZOIC	Devonian	Lower Devonian	Beartooth Butte Formation[2]								
PALEOZOIC	Silurian[6]										
PALEOZOIC	Ordovician	Upper Ordovician; Lower Ordovician	Bighorn Dolomite; Harding Sandstone equivalent		Major aquifer		Principal aquifer			Major aquifer–limestone	Bighorn aquifer
PALEOZOIC	Cambrian	Upper Cambrian	Gallatin Limestone and equivalent		Regional aquitard	Major regional confining unit	Leaky confining units	Confining unit	Confining unit (Gallatin–Gros Ventre confining unit)	Minor aquifer	Gallatin confining unit; Gallatin–Gros Ventre confining unit
PALEOZOIC	Cambrian	Middle Cambrian	Gros Ventre Formation and equivalent							Minor aquifer	Gros Ventre confining unit
PALEOZOIC	Cambrian	Middle Cambrian	Flathead Sandstone		Major aquifer (Flathead aquifer)	Principal aquifer (Flathead aquifer)	Principal aquifer	Major aquifer	Aquifer (Flathead aquifer)	Major aquifer–limestone[5]	Flathead aquifer
Precambrian			Precambrian rocks	7				Basal confining unit		Major aquitard	Precambrian basal confining unit

[1]Pliocene rocks not present in Bighorn Basin.

[2]Function of lithostratigraphic unit as hydrogeologic unit not defined.

[3]Park City Formation considered equivalent to all or parts of Phosphoria and Goose Egg Formations.

[4]Function of Muddy Sandstone as hydrogeologic unit not defined in WWC Engineering et al. (2007, fig. 4-9).

[5]Predominant lithology of formation is sandstone, and it is unknown why formation is defined as "Major aquifer–limestone" in WWC Engineering et al. (2007, fig. 4-9).

[6]Silurian rocks not present in Bighorn Basin.

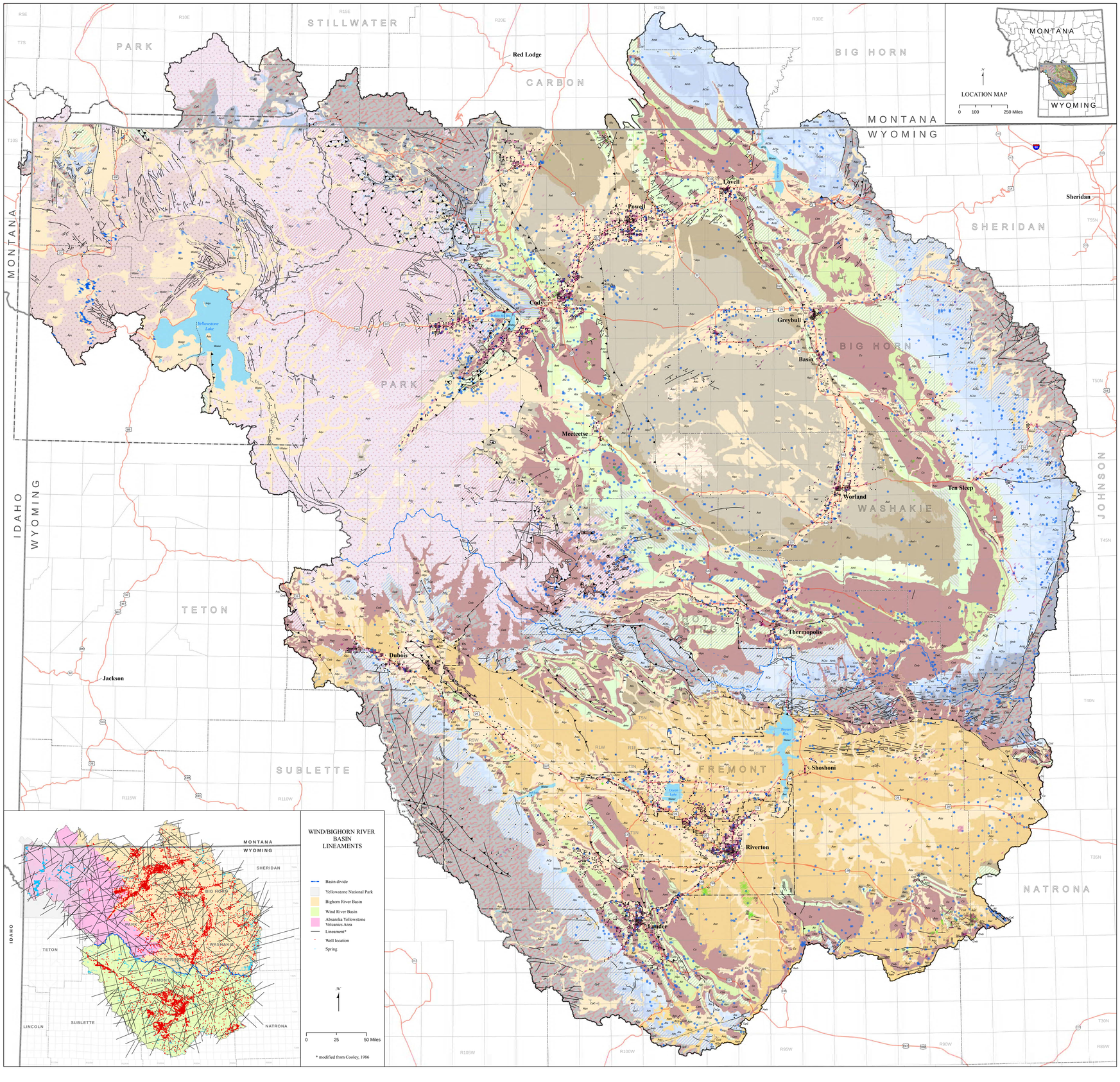
[7]Tertiary, Mesozoic, and Paleozoic sedimentary-rock hydrogeologic units identified as continuing under the Absaroka Range and Yellowstone Volcanic Area.

Abbreviations used in the columns:

c.u. Confining unit
Fm Formation
Ss Sandstone
Mbr Member

Modified from Lowry et al. (1976); Libra et al. (1981); Western Water Consultants, Inc. (1982a,b; 1983b); Cooley (1984, 1986); Doremus (1986); Jarvis (1986a); Spencer (1986a); Love et al. (1993); and WWC Engineering et al. (2007)

Plate III. Relation of lithostratigraphic units to hydrogeologic units, Bighorn Basin, Wyoming.



Surface Hydrogeology
Wind/Bighorn River Basin
Wyoming and Montana

with
Wyoming State Engineer's Office
Permitted and Completed Wells through 2009

compiled
by
Nikolaus Gribb, Brett Worman, Scott Quillinan,
Tomas Gracias, and Tim Bartos

2012

N

0 5 10 20 30 Miles

Scale 1:380,000
1 inch equals approximately 6 miles

Explanation

- Interstate highway
- 14 US highway
- 243 State highway
- Normal fault - location certain
- Normal fault - location concealed } barbell on downthrown side
- Thrust fault - location certain
- Thrust fault - location concealed } sawteeth on upper plate
- Gravity slide masses related to Heart Mountain, South Fork, and eastern/southeastern Absaroka displacements
- Wind River/Bighorn River Basin hydrologic divide
- State boundary
- County boundary
- Township and Range boundaries
- Wind River Indian Reservation boundary
- Yellowstone National Park boundary
- Spring
- Industrial, Coalbed Natural Gas, Mineral, or Commercial well
- Miscellaneous well
- Monitoring well
- Agricultural (Livestock and Irrigation) well
- Domestic, Municipal, or Public well

Surface Hydrogeology

(See **Plates II, III, and V** for geologic units correlations.)

Bighorn River Basin and Absaroka-Yellowstone Volcanics Hydrogeologic Units

CENOZOIC

- Water
- Aqu Quaternary unconsolidated deposit aquifers
- Undefined volcanic hydrogeologic units
- Undefined Tertiary hydrologic units
- Ayr Yellowstone Group aquifer
- Aav Absaroka Volcanic Supergroup aquifer
- Awh White River aquifer
- Cwb Wagon Bed confining unit
- Awl Willwood aquifer
- Afu Fort Union aquifer

MESOZOIC

Lower Tertiary/Upper Cretaceous aquifer system

- Undefined Mesozoic hydrologic units
- Alu Lance aquifer
- Amt Meeteetse aquifer and confining unit
- Amv Mesaverde aquifer

Lower and middle Mesozoic aquifers and confining units

- Cc Cody confining unit
- Afr Frontier aquifer
- Cmt Mowry–Thermopolis confining unit
- Undifferentiated Mesozoic geologic units (May include: Mowry–Thermopolis c.u., Muddy Sandstone aq., Cloverly aq., Morrison c.u. and aq., Sundance c.u. and aq., Gypsum Spring c.u. and aq., Nugget aq.)
- Cbd Chugwater–Dinwoody aquifer and confining unit
- Undifferentiated Mesozoic/Paleozoic geologic units

PALEOZOIC

- Undifferentiated Paleozoic geologic units (May include: Goose Egg–Phosphoria aq. and c.u., Amsden c.u., Madison–Bighorn aq., Gallatin–Gros Ventre c.u.)

Paleozoic aquifer system

- ACp Goose Egg–Phosphoria aquifer and confining unit
- ACte Tensleep aquifer and Amsden confining unit
- Amb Madison–Bighorn aquifer
- Ag Gallatin–Gros Ventre confining unit and Flathead aquifer

PRECAMBRIAN

- CpC Precambrian basal confining unit

Wind River Basin Hydrogeologic Units

CENOZOIC

- Glacial ice
- Water
- Aqu Quaternary unconsolidated deposit aquifers
- Undefined volcanic hydrogeologic units
- Asr Split Rock aquifer
- Awh White River aquifer
- Aav Absaroka Volcanic Supergroup aquifer
- Cwb Aycross–Wagon Bed confining unit
- Undifferentiated Tertiary geologic units (May include Aycross–Wagon Bed c.u., Wind River aq.)
- Awr Wind River aquifer
- Cim Indian Meadows confining unit

Fort Union–Lance aquifer

- Afu Fort Union aquifer

MESOZOIC

- Alu Lance aquifer
- Cmt Meeteetse–Lewis confining unit
- Amv Mesaverde aquifer
- Cc Cody confining unit

Lower and middle Mesozoic aquifers and confining units

- Afr Frontier aquifer
- Undifferentiated Mesozoic geologic units (May include: Frontier aq., Mowry–Thermopolis c.u., Muddy Sandstone aq., Cloverly aq., Morrison c.u., Sundance–Nugget aq., Gypsum Spring c.u.)
- Cmt Mowry–Thermopolis confining unit
- Asn Sundance–Nugget aquifer
- Cbd Chugwater–Dinwoody aquifer and confining unit

PALEOZOIC

- ACp Goose Egg–Phosphoria aquifer and confining unit
- Undifferentiated Mesozoic/Paleozoic geologic units

Paleozoic aquifer system

- Ate Tensleep and Amsden aquifers
- Undifferentiated Paleozoic geologic units (May include: Madison aq., Darby aq., Bighorn aq., Gallatin–Gros Ventre c.u.)
- Amb Bighorn aquifer
- Ag Gallatin–Gros Ventre confining unit and Flathead aquifer

PRECAMBRIAN

- CpC Precambrian basal confining unit

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	Plate I				Plate III	Plate II		Plates IV and X			
	Geologic unit				Wyoming lithostratigraphic unit(s)		Montana lithostratigraphic unit(s) as named for their Wyoming equivalents	Hydrogeologic Unit			
	Symbol		Age & general lithology	Wyoming state map unit	Bighorn Basin	Wind River Basin		Bighorn Basin and Absaroka/Yellowstone Volcanic unit		Wind River Basin and Absaroka/Yellowstone Volcanic unit	
	Wyoming	Montana#									
CENOZOIC UNITS											
	Water	Water	Water (surface)	Water (surface)	Water (surface)	Water (surface)	Water (surface)	Aqu		Aqu	Quaternary unconsolidated deposit aquifers
	Ice	–	Glacial ice	Glacial ice	–	Glacial ice	–				
Quaternary units	Qa	Qa	Pleistocene-Holocene alluvium & colluvium	Alluvium & colluvium	Alluvium & colluvium	Alluvium & colluvium	Alluvium & colluvium	Aqu	Quaternary unconsolidated deposit aquifers		
	Qt	Qt	Pleistocene-Holocene unconsolidated deposits	Gravel, pediment, & fan deposits	Gravel, pediment, & fan deposits	Gravel, pediment, & fan deposits	Gravel, pediment, & fan deposits				
	Qg	Qg	Pleistocene-Holocene glacial deposits	Glacial deposits	Glacial deposits	Glacial deposits	Glacial deposits				
	Qls*	–	Pleistocene-Holocene landslide & glacial drift	Landslide deposits	Landslide deposits	Landslide deposits	–				
	Qs	–	Pleistocene-Holocene dune sand & loess	Dune sand & loess deposits	–	Dune sand & loess deposits	–				
	Ql*	–	Pleistocene-Holocene clay, silt, & fine sand	Playa lake or marine deposits	–	Playa lake or marine deposits	–				
	Qu	Qu	Pleistocene-Holocene alluvium & colluvium deposits	Undivided surficial deposits	Undivided surficial deposits	–	Undivided surficial deposits	Aqu	Quaternary unconsolidated deposit aquifers		
	Qb	–	Pleistocene basalt & intrusive rocks	Basalt flows & intrusive igneous rocks	Basalt flows & intrusive igneous rocks	Basalt flows & intrusive igneous rocks	–		undefined volcanic hydrogeologic unit(s)[2]		undefined volcanic hydrogeologic unit(s)[2]
	Qr	–	Pleistocene rhyolite & lava flow rocks	Rhyolite flows, tuff, & intrusive igneous rocks	Rhyolite flows, tuff, & intrusive igneous rocks	–	–	Ayv	Yellowstone Volcanic Group		
	QTg	–	Pliocene-Pleistocene gravel deposit	Terrace gravels	Terrace gravels	–	–	Aqu	Quaternary unconsolidated deposit aquifers		
Tertiary units	Thr	Thr	Pliocene rhyolite & tuff rocks	Huckleberry Ridge Tuff of Yellowstone Group	Huckleberry Ridge Tuff of Yellowstone Group	–	Huckleberry Ridge Tuff of Yellowstone Group	Ayv	Yellowstone Volcanic Group		
	Tii	–	Miocene-Pliocene granitoid & basalt rocks	Intrusive & extrusive igneous rocks	Intrusive & extrusive igneous rocks	–	–		undefined volcanic hydrogeologic unit(s)[2]		
	Tcv	–	Miocene-Pliocene dacitic & felsic volcanic rocks	Caldwell Canyon Volcanics	–	Caldwell Canyon Volcanics	–				undefined volcanic hydrogeologic unit(s)[2]
	Tmu	–	Upper Miocene sandstone & claystone	Upper Miocene rocks (undivided)	–	Upper Miocene rocks (undivided)	–			Asr	Split Rock aquifer
	Tm	–	Miocene sandstone & conglomerate	Miocene rocks (undivided)	–	Miocene rocks (undivided)	–				
	Tml	–	Lower Miocene sandstone (includes Split Rock Formation)	Lower Miocene (undivided)	Lower Miocene (undivided)	Lower Miocene (undivided)	–		undefined Tertiary hydrogeologic unit(s)[2]		
	Twr	–	Oligocene fine & medium-grained mixed clastic	White River Formation	White River Formation	White River Formation	–	Awh	White River aquifer	Awh	White River aquifer
	Ti	Ti	Eocene plutonic rocks	Intrusive igneous rocks	Intrusive igneous rocks	Intrusive igneous rocks	Intrusive igneous rocks		undefined Tertiary hydrogeologic unit(s)[2]		undefined Tertiary hydrogeologic unit(s)[2]
	Tta	Tta	Eocene andesitic & pyroclastic rocks	Thorofare Creek & Sunlight Groups	Thorofare Creek & Sunlight Groups	–	Thorofare Creek & Sunlight Groups				
	Twi	–	Eocene mixed clastic/volcanic rocks	Wiggins Formation	Wiggins Formation	Wiggins Formation	–	Aav	Absaroka Volcanic Supergroup	Aav	Absaroka Volcanic Supergroup
	Ttl	–	Eocene mixed clastic/volcanic & intermediate volcanic rocks	Two Ocean & Langford Formations	Two Ocean & Langford Formations	–	–				
	Tt	–	Eocene mixed clastic/volcanic & medium-grained mixed clastic	Tepee Trail Formation	Tepee Trail Formation	Tepee Trail Formation	–		undefined volcanic hydrogeologic unit(s)[2]	Cwb	Aycross-Wagon Bed confining unit
	Ta	–	Eocene mixed clastic/volcanic & fine-grained mixed clastic	Aycross Formation	Aycross Formation	Aycross Formation	–				
	Ts	Ts	Eocene intermediate volcanic & basalt rocks	Crescent Hill Basalt of Sunlight Group	Crescent Hill Basalt of Sunlight Group	–	Crescent Hill Basalt of Sunlight Group	Aav	Absaroka Volcanic Supergroup		
	Ttp	–	Eocene trachyandesite rocks	Trout Peak Trachyandesite	Trout Peak Trachyandesite	–	–				
	Twp	Twp	Eocene mixed clastic/volcanic & intermediate volcanic rocks	Wapiti Formation	Wapiti Formation	–	Wapiti Formation		undefined volcanic hydrogeologic unit(s)[2]		
	Tpw	Tpw	Eocene mixed clastic/volcanic & intermediate volcanic rocks	Washburn Group	Washburn Group	–	Washburn Group	Aav	Absaroka Volcanic Supergroup		
	Twb	–	Eocene claystone & conglomerate	Wagon Bed Formation	Wagon Bed Formation	Wagon Bed Formation	–	Awb	Wagon Bed aquifer	Cwb	Aycross-Wagon Bed confining unit
	Tv	–	Eocene conglomerate & mixed elastic/volcanic rocks	Volcanic conglomerate	–	Volcanic conglomerate	–				undefined volcanic hydrogeologic unit(s)[2]
	Tcr	–	Eocene conglomerate	Crandall Conglomerate	Crandall Conglomerate	–	–		undefined Tertiary hydrogeologic unit(s)[2]		
	Twrd	–	Eocene claystone & siltstone	Wind River Formation	–	Wind River Formation	–			Awr	Wind River aquifer
	Twrp	–	Eocene fine-grained mixed clastic & medium-grained mixed clastic rocks	Wind River & Indian Meadows Formations	–	Wind River & Indian Meadows Formations	–				undifferentiated Tertiary geologic unit(s)[1]
	Tim	–	Eocene fine-grained mixed clastic & medium-grained mixed clastic rocks	Indian Meadows Formation	Indian Meadows Formation	Indian Meadows Formation	–		undefined Tertiary hydrogeologic unit(s)[2]	Cim	Indian Meadows confining unit
	Tta	–	Eocene fine-grained mixed clastic & oil shale rocks	Tatman Formation	Tatman Formation	–	–				
	Twl	Twl	Eocene fine-grained mixed clastic & medium-grained mixed clastic rocks	Willwood Formation	Willwood Formation	–	Willwood Formation	Awl	Willwood aquifer		
	Ttu	Ttu	Paleocene sandstone & shale	Fort Union Formation	Fort Union Formation	Fort Union Formation	Fort Union Formation	Atu	Fort Union aquifer	Atu	Fort Union aquifer
	TKu	–	Upper Cretaceous & Paleocene sandstone & shale	Sedimentary rocks	–	Sedimentary rocks	–				undifferentiated Tertiary geologic unit(s)[1]
MESOZOIC UNITS											
	Ki	–	Cretaceous plutonic rocks	Intrusive igneous rocks	Intrusive igneous rocks	–	–		undefined Mesozoic hydrogeologic unit(s)[2]		
	Klc	–	Upper Cretaceous sandstone & conglomerate	Landslide Creek Formation	Landslide Creek Formation	–	–				
	Kha	–	Upper Cretaceous sandstone & conglomerate	Harebell Formation	Harebell Formation	–	–				
Cretaceous units	Kl	Kl	Upper Cretaceous sandstone & shale	Lance Formation	Lance Formation	Lance Formation	Lance Formation	Ala	Lance aquifer	Ala	Lance aquifer
	Klm	–	Upper Cretaceous medium-grained mixed clastic & fine-grained mixed clastic rocks	Lewis Shale & Bearpaw Formation	Lewis Shale & Bearpaw Formation	Lewis Shale & Bearpaw Formation	–		undifferentiated Mesozoic geologic unit(s)[1]		undifferentiated Mesozoic geologic unit(s)[1]
	Kms	Kms	Upper Cretaceous sandstone & claystones	Meeteetse Formation	Meeteetse Formation	Meeteetse Formation	Meeteetse Formation	Amt	Meeteetse aquifer & confining unit	Cml	Meeteetse-Lewis confining unit
	Kml	–	Upper Cretaceous medium-grained mixed clastic & fine-grained mixed clastic rocks	Meeteetse Formation & Lewis Shale	–	Meeteetse Formation & Lewis Shale	–				
	Kle	–	Upper Cretaceous shale & sandstone	Lewis Shale	–	Lewis Shale	–				
	Ket	–	Upper Cretaceous sandstone & shale	Everts Formation, Eagle Sandstone, & Telegraph Creek Formation	Everts Formation, Eagle Sandstone, & Telegraph Creek Formation	–	–		undefined Mesozoic hydrogeologic unit(s)[2]		
	Kb	–	Upper Cretaceous sandstone & coal	Bacon Ridge Sandstone	Bacon Ridge Sandstone	–	–				
	Kmv	Kmv	Upper Cretaceous sandstone & shale	Mesaverde Group	Mesaverde Group	Mesaverde Group	Mesaverde Group	Amv	Mesaverde aquifer	Amv	Mesaverde aquifer
	Kc	Kc	Upper Cretaceous shale & sandstone	Cody Shale	Cody Shale	Cody Shale	Cody Shale	Cc	Cody Shale confining unit	Cc	Cody Shale confining unit
	Kf	Kf	Upper Cretaceous sandstone & shale	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation	Afr	Frontier aquifer	Afr	Frontier aquifer
	Klt	–	Upper-Lower Cretaceous sandstone & shale	Frontier Formation, Mowry Shale, & Thermopolis Shale	Frontier Formation, Mowry Shale, & Thermopolis Shale	Frontier Formation, Mowry Shale, & Thermopolis Shale	–		undifferentiated Mesozoic geologic unit(s)[1]		undifferentiated Mesozoic geologic unit(s)[1]
	Kmt	Kmt	Lower Cretaceous shale & sandstone	Mowry Shale, Muddy Sandstone, & Thermopolis Shale	Mowry Shale, Muddy Sandstone, & Thermopolis Shale	Mowry Shale, Muddy Sandstone, & Thermopolis Shale	Mowry Shale, Muddy Sandstone, & Thermopolis Shale	Ctm	Thermopolis-Mowry confining unit	Ctm	Thermopolis-Mowry confining unit
Jurassic units	KJ	KJ	Jurassic-Lower Cretaceous sandstone & claystone	Cloverly & Morrison Formations	Cloverly & Morrison Formations	Cloverly & Morrison Formations	Cloverly & Morrison Formations		undifferentiated Mesozoic geologic unit(s)[1]		undifferentiated Mesozoic geologic unit(s)[1]
	KJs	–	Middle Jurassic-Lower Cretaceous fine-grained mixed clastics & medium-grained mixed clastics	Cloverly & Morrison & Sundance Formations	Cloverly & Morrison & Sundance Formations	Cloverly & Morrison & Sundance Formations	–				
	KJg	KJg	Middle Jurassic-Lower Cretaceous fine-grained clastics & medium-grained mixed clastics	Cloverly & Morrison & Sundance & Gypsum Spring Formations	Cloverly & Morrison & Sundance & Gypsum Spring Formations	Cloverly & Morrison & Sundance & Gypsum Spring Formations	Cloverly & Morrison & Sundance & Gypsum Spring Formations				
	KJk	–	Middle Jurassic-Lower Cretaceous fine-grained mixed clastics & medium-grained mixed clastics	Ellis Group & Morrison & Kootenai Formations	Ellis Group & Morrison & Kootenai Formation	–	–				
	KTR	–	Middle Jurassic-Lower Cretaceous sandstone & shale	Cloverly, Morrison, & Sundance Formations	–	Cloverly, Morrison, & Sundance Formations	–				undifferentiated Mesozoic geologic unit(s)[1]
	Js	–	Upper Triassic-Middle Jurassic sandstone & shale	Sundance Formation	–	Sundance Formation	–			Asn	Sundance-Nugget aquifer
	Jsg	Jsg	Middle Jurassic-Lower Cretaceous sandstone & shale	Sundance & Gypsum Spring Formations	Sundance & Gypsum Spring Formations	Sundance & Gypsum Spring Formations	Sundance & Gypsum Spring Formations		undifferentiated Mesozoic geologic unit(s)[1]		undifferentiated Mesozoic geologic unit(s)[1]
	JTR	–	Upper Triassic(?)-Middle Jurassic(?) sandstone & shale	Sundance, Gypsum Spring, & Nugget Formation	Sundance, Gypsum Spring, & Nugget Formation	Sundance, Gypsum Spring, & Nugget Formation	–				
	JTRgn	–	Triassic(?)-Upper Jurassic sandstone & fine-grained mixed clastics	Gypsum Spring Formation & Nugget Sandstone	–	Gypsum Spring Formation & Nugget Sandstone	–				
	JTRgc	–	Lower Triassic-Upper Jurassic fine-grained mixed clastic and carbonate rocks	Gypsum Spring Formation, Nugget Sandstone, & Chugwater Formation	Gypsum Spring Formation, Nugget Sandstone, & Chugwater Formation	–	–		undifferentiated Mesozoic geologic unit(s)[1]		
	JTRn	–	Triassic(?)-Jurassic sandstone	Nugget sandstone	–	Nugget sandstone	–			Asn	Sundance-Nugget aquifer
Triassic units	Trc	Trc	Lower-Upper Triassic siltstone & shale	Chugwater Formation	Chugwater Formation	Chugwater Formation	Chugwater Formation	Ccd	Chugwater-Dinwoody confining unit	Ccd	Chugwater-Dinwoody aquifer & confining unit
	Trcd	–	Lower-Upper Triassic mudstone & limestone	Chugwater & Dinwoody Formations	Chugwater & Dinwoody Formations	Chugwater & Dinwoody Formations	–				
	TRPcg	–	Permian & Lower Triassic sandstone & siltstone	Chugwater & Goose Egg Formations	Chugwater & Goose Egg Formations	–	–		undifferentiated Mesozoic & Paleozoic geologic unit(s)[1]		
	TRPg	TRPg	Permian & Lower Triassic sandstone & siltstone	Goose Egg Formation	Goose Egg Formation	Goose Egg Formation	Goose Egg Formation	ACp	Phosphoria-Goose Egg aquifer & confining unit	ACp	Phosphoria-Goose Egg aquifer & confining unit
PALEOZOIC UNITS											
	MzPz	MzPz	Upper Mississippian-Lower Cretaceous sedimentary units & clastics	Mesozoic & Paleozoic rocks (undivided)	Mesozoic & Paleozoic rocks (undivided)	Mesozoic & Paleozoic rocks (undivided)	Mesozoic & Paleozoic rocks (undivided)		undifferentiated Mesozoic & Paleozoic geologic units[1]		undifferentiated Mesozoic & Paleozoic geologic units[1]
	Pp	Pp	Permian shale & phosphorite rocks	Phosphoria Formation & related rocks	Phosphoria Formation & related rocks	Phosphoria Formation & related rocks	Phosphoria Formation & related rocks	ACp	Phosphoria-Goose Egg aquifer & confining unit	ACp	Phosphoria-Goose Egg aquifer & confining unit
	PPMa	–	Upper Mississippian-Permian limestone & sandstone	Phosphoria Formation & related rocks, Quadrant Sandstone, & Amsden Formation	Phosphoria Formation & related rocks, Quadrant Sandstone, & Amsden Formation	–	–		undifferentiated Paleozoic geologic unit(s)[1]		
	PM	PM	Upper Mississippian-Permian sandstone & carbonate	Tensleep Sandstone & Amsden Formation	Tensleep Sandstone & Amsden Formation	Tensleep Sandstone & Amsden Formation	Tensleep Sandstone & Amsden Formation	ACta	Tensleep aquifer & Amsden confining unit	Ata	Tensleep aquifer & Amsden aquifer
	Pzr	–	Cambrian-Permian limestone, & dolostone	Paleozoic rocks (undivided)	–	Paleozoic rocks (undivided)	–				undifferentiated Paleozoic geologic unit(s)[1]
	Mm	Mm	Lower-Upper Mississippian limestone & dolostone(dolomite)	Madison Limestone or Group	Madison Limestone or Group	Madison Limestone or Group	Madison Group			Am	Madison aquifer
	MD	MD	Upper Devonian-Upper Mississippian limestone & dolomite	Madison Group, Darby or Three Forks, & Jefferson Formations	Madison Group, Three Forks, & Jefferson Formations	Madison Limestone & Darby Formation	Madison Group				undifferentiated Paleozoic geologic unit(s)[1]
	MO	–	Middle Ordovician Upper Mississippian limestone and dolostone (dolomite)	Madison Limestone and Bighorn Dolomite	Madison Limestone and Bighorn Dolomite	–	–	Amb	Madison-Bighorn aquifer		
	MDO	–	Lower Mississippian-Ordovician limestone or dolomite	Madison Limestone, Darby or Three Forks, Jefferson, & Beartooth Butte Formations & Bighorn Dolomite	Madison Limestone, Darby or Three Forks, Jefferson, & Beartooth Butte Formations & Bighorn Dolomite	–	–				
	DO	DO	Upper Devonian-Middle Ordovician carbonate rock & mudstone	Three Forks, Jefferson, & Beartooth Formations & Bighorn Dolomite	Three Forks, Jefferson, & Beartooth Formations & Bighorn Dolomite	–	Three Forks, Jefferson, & Beartooth Formations & Bighorn Dolomite				
	Ob	Ob	Upper & middle Ordovician dolostone(dolomite)	Bighorn Dolomite	Bighorn Dolomite	–	Bighorn Dolomite				
	OC	OC	Middle Cambrian-Upper Ordovician limestone & dolostone(dolomite)	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation & Flathead Sandstone	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation & Flathead Sandstone	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation & Flathead Sandstone	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation & Flathead Sandstone		undifferentiated Paleozoic geologic unit(s)[1]		undifferentiated Paleozoic geologic unit(s)[1]
	Cr	Cr	Middle-Upper Cambrian limestone & sandstone	Gallatin Limestone, Gros Ventre Formation & Equivalents & Flathead Sandstone	Gallatin Limestone, Gros Ventre Formation & Equivalents & Flathead Sandstone	Gallatin Limestone, Gros Ventre Formation & Equivalents & Flathead Sandstone	Gallatin Limestone, Gros Ventre Formation & Equivalents & Flathead Sandstone	Afl	Gallatin-Gros Ventre confining unit & Flathead aquifer	Afl	Gallatin-Gros Ventre confining unit & Flathead aquifer
PRECAMBRIAN UNITS											
	pЄr	pЄr	Early-Late Archean granitic gneiss, metasedimentary & metavolcanic rocks, granodiorite, granitoid, and quartz monzonite	Precambrian rocks	Precambrian rocks	Precambrian rocks	Precambrian rocks	CpЄ	Precambrian basal confining unit(s)	CpЄ	Precambrian basal confining unit(s)

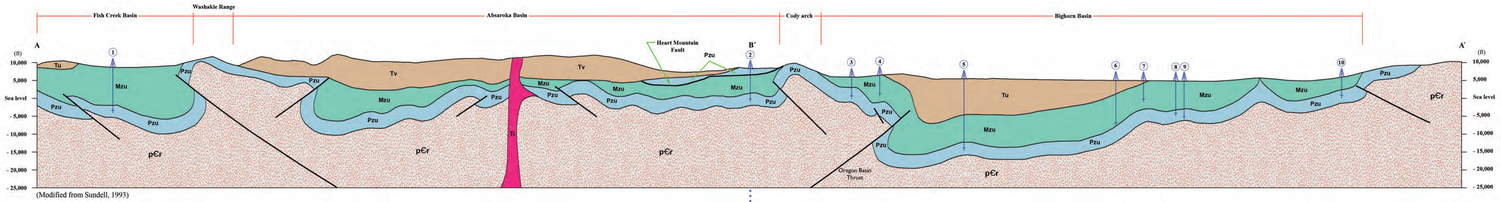
#Montana lithostratigraphic units as named for their Wyoming equivalents
[1] Lithostratigraphic unit is undifferentiated on the Wyoming state map.
[2] Function of lithostratigraphic unit as hydrogeologic unit is not defined.

References: Plates II & III of this report

Geologic units and corresponding lithostratigraphic units and hydrogeologic units, Wind/Bighorn River Basin, Wyoming and Montana.

compiled by
Nikolaus Gribb, Brett N. Worman, and Tomas Gracias

2012



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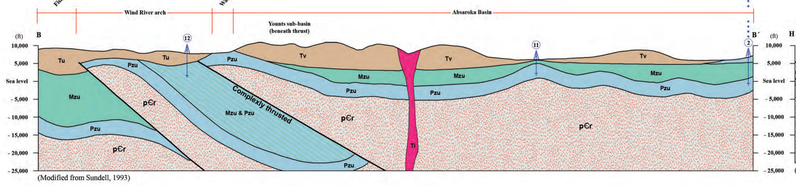

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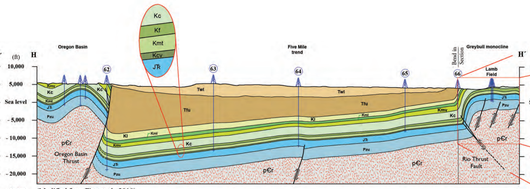

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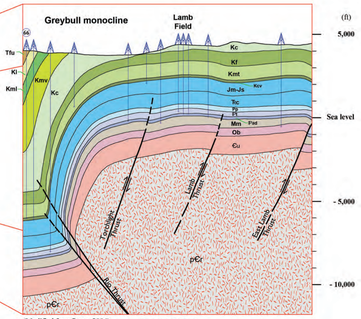

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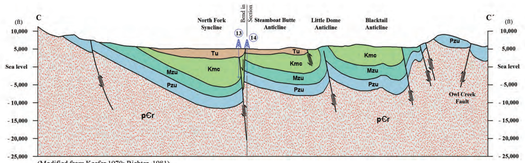

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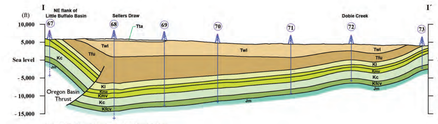

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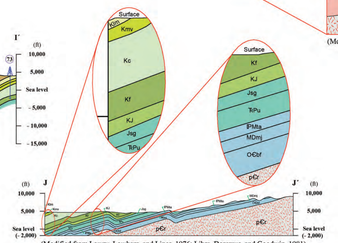

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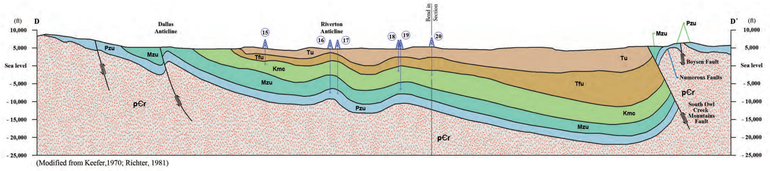

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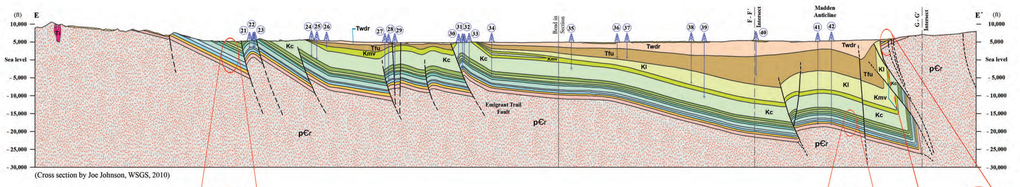
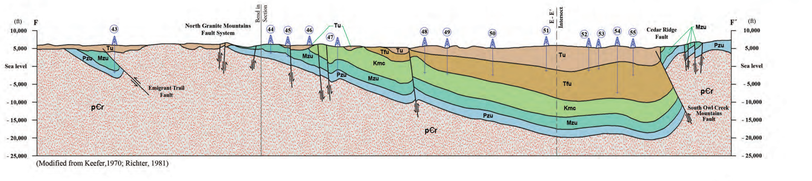


(Cross section by Joe Johnson, WSGS, 2010)



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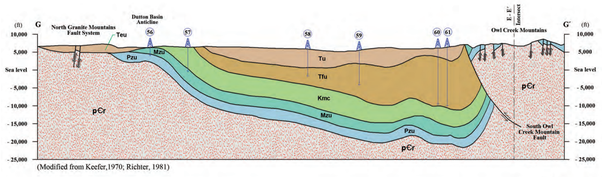


(Modified from Keefer,1970; Richter, 1981)

EXPLANATION

CROSS SECTION SYMBOLS

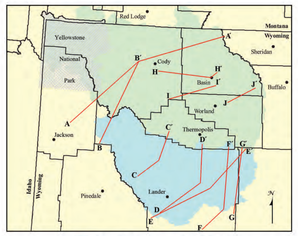
Formation contact

Fault - Dashed where inferred; arrows indicate relative movement

Drill hole - Well logs used to construct cross sections

GEOLOGY

Tu	Tertiary rocks undivided (Post-Fort Union Formation)
Tv	Tertiary volcanics
Ti	Tertiary intrusives
Teu	Lower Eocene and younger Tertiary rocks undivided
Twr	White River Formation
Twb	Wagon Bed Formation
Tta	Tatman Formation
Twdr	Wind River Formation
Twl	Willwood Formation
Tfu	Fort Union Formation
Mzu	Mesozoic rocks undivided
Kl	Lance Formation
Klm	Lance and Meeteetse Formations
Kme	Meeteetse Formation
Kml	Meeteetse Formation and Lewis Shale
Kmv	Mesaverde Formation
Kmc	Meeteetse and Mesaverde Formations and Cody Shale undivided
Kc	Cody Shale
Kf	Frontier Formation
Kfcv	Frontier Formation through Cloverly Group undivided
Kmr	Mowry Shale
Kmt	Mowry Shale, Muddy Sandstone, and Thermopolis Shale undivided
Kcv	Cloverly Formation
KJ	Cloverly and Morrison Formations undivided
Jm	Morrison Formation
Jm-Js	Morrison, Sundance and Gypsum Spring Formations
Jsg	Sundance and Gypsum Spring Formations
JTR	Sundance and Gypsum Spring Formations and Nugget Sandstone undivided
Ttc	Chugwater Formation
Ttcd	Chugwater and Dinwoody Formations
TRPu	Triassic and Permian rocks undivided
Pzu	Paleozoic rocks undivided
Pp	Phosphoria Formation
IPt	Tensleep Sandstone
IPMta	Tensleep Sandstone and Amsden Formation
IPad	Darwin Sandstone Member of Amsden Formation
Mm	Madison Limestone
MDmj	Madison Limestone, Jefferson, and Three Forks Formations
MDO	Mississippian, Devonian, and Ordovician units
Ob	Bighorn Dolomite
OЄbf	Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone
Єu	Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone undivided
pЄr	Precambrian igneous and metamorphic rocks



INDEX MAP

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WELL CONTROL ALONG CROSS SECTIONS

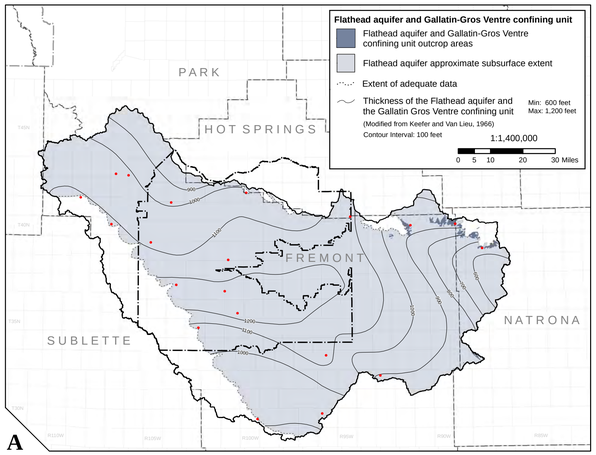
Well No.	Agi No.	Operator	Well Name	Bottom Formation	Surface Location sec.	T.	R.	Basin	County	Spud Year
1	49-039-20037	Exxon Mobil Corporation	Leidy Creek Federal 2	Gallatin	2	44 N	113 W	Jackson Hole	Teton	(1986)
2	49-029-21478	Phillips Petroleum Company	Buff Bill A W-73305 1	Amsden	26	53 N	104 W	Bighorn	Park	(1987)
3	49-029-05856	Conoco Inc.	McAlpin W-86354-B 1	Madison	10	53 N	102 W	Bighorn	Park	(1955)
4	49-029-21048	Marathon Oil Company	Bassett Fee 1-1	Frontier	1	53 N	102 W	Bighorn	Park	(1981)
5	49-029-05872	Husky Oil Company	McCulloch Peak Unit 1	Madison	21	54 N	100 W	Bighorn	Park	(1949)
6	49-029-05885	Conoco Inc.	Conoco Farwell Pat 1	Madison	1	54 N	98 W	Bighorn	Park	(1963)
7	49-003-20685	Washakie Oil Company	Washakie Crosby 1	Mowry	15	55 N	97 W	Bighorn	Big Horn	(1983)
8	49-003-20023	Tenneco Oil Company	Mildred Snyder 2	Phosphoria	8	55 N	96 W	Bighorn	Big Horn	(1967)
9	49-003-05943	Colorado Oil & Gas Corporation	Federal 1X	Madison	9	55 N	96 W	Bighorn	Big Horn	(1957)
10	49-003-06442	Kramer Harold G	Federal W-095412 1	Madison	7	56 N	93 W	Bighorn	Big Horn	(1961)
11	49-029-21468	Snyder Oil Corporation	Ishawooa W-54499 1-7	Gallatin	7	49 N	105 W	Bighorn	Park	(1986)
12	49-013-21368	Chevron USA Inc.	Chevron-Federal 2-17	Tensleep	17	43 N	108 W	Wind River	Fremont	(1983)
13	49-013-06468	British American Oil	Tribal Q 1	Cody	30	4 N	1 W	Wind River	Fremont	(1952)
14	49-013-06469	Marathon Oil Company	Tribal C-14	Tensleep	30	4 N	1 W	Wind River	Fremont	(1952)
15	49-013-05705	Atlantic Richfield Company	Federal-646-Fremont 2	Cody	10	33 N	97 W	Wind River	Fremont	(1963)
16	49-013-05922	Devon Energy Production Company LP	Riverton Tribal 4	Tensleep	36	1 S	4 E	Wind River	Fremont	(1951)
17	49-013-20261	Hudson Group LLC	Tribal 6	Wind River	30	1 S	5 E	Wind River	Fremont	(1970)
18	49-013-06002	BP America Production Company	Shoshone 1	Cody	1	1 S	5 E	Wind River	Fremont	(1949)
19	49-013-06004	Peak Wyoming Acquisition LCC	Tribal 1	Morrison	1	1 S	5 E	Wind River	Fremont	(1964)
20	49-013-06035	Farmers Union Exchange	Shoshone-Arapahoe 1	Cody	28	1 S	6 E	Wind River	Fremont	(1959)
21	49-013-21383	Hrubetz Oil Company	Dallas-Federal 1-19	Tensleep	19	32 N	98 W	Wind River	Fremont	(1983)
22	49-013-06936	Sunset International	Govt 29-4B	Tensleep	29	32 N	98 W	Wind River	Fremont	(1966)
23	49-013-05367	Cabeen Exploration	Govt 1	Tensleep	19	32 N	98 W	Wind River	Fremont	(1957)
24	49-013-21915	Sauer Bill Oil & Gas Company LLC	Sauer Ogle 1	Frontier	7	32 N	97 W	Wind River	Fremont	(1999)
25	49-013-05490	Conoco Inc.	Govt 2	Morrison	8	32 N	97 W	Wind River	Fremont	(1956)
26	49-013-22204	Phillips Petroleum Company	Cornhole 2	Mesaverde	28	33 N	97 W	Wind River	Fremont	(2001)
27	49-013-05623	Devon Energy Production Company LP	Beaver Creek Unit 10	Phosphoria	16	33 N	96 W	Wind River	Fremont	(1948)
28	49-013-05639	Devon Energy Production Company LP	Beaver Creek Unit 55	Tensleep	16	33 N	96 W	Wind River	Fremont	(1958)
29	49-013-05649	Devon Energy Production Company LP	Beaver Creek Unit 40	Cambrian	10	33 N	96 W	Wind River	Fremont	(1955)
30	49-013-20381	Texaco Exploration & Prod.	Govt-P L Ackerman 1	Skull Creek	27	34 N	95 W	Wind River	Fremont	(1972)
31	49-013-20334	Legacy Reserves Operating LP	Alkali Butte Unit 8	Madison	26	34 N	95 W	Wind River	Fremont	(1971)
32	49-013-20547	Legacy Reserves Operating LP	Federal 1	Thermopolis	23	34 N	95 W	Wind River	Fremont	(1975)
33	49-013-05903	M K M Oil Company	Hagood 1	Thermopolis	23	34 N	95 W	Wind River	Fremont	(1959)
34	49-013-20184	Occidental	Govt-Campbell Ridge 1	Morrison	7	34 N	94 W	Wind River	Fremont	(1969)
35	49-013-05997	Swepi LP	Conant Creek Unit 22-27	Cody	27	35 N	93 W	Wind River	Fremont	(1962)
36	49-013-21347	ANR Production Company	Conant Creek Unit 1-6	Fort Union	6	35 N	92 W	Wind River	Fremont	(1982)
37	49-013-21454	Amerada Hess Corporation	Federal 30-23	Fort Union	30	36 N	92 W	Wind River	Fremont	(1984)
38	49-013-22427	Encana Oil and Gas USA Inc.	Riverbank Unit 1	Meeteetse	31	37 N	91 W	Wind River	Fremont	(2004)
39	49-013-20845	Dome Petroleum Corporation	Moneta Unit 1-29	Shannon	29	37 N	91 W	Wind River	Fremont	(1978)
40	49-013-21820	Noble Energy Inc.	State 44-36	Fort Union	36	38 N	91 W	Wind River	Fremont	(1997)
41	49-013-21510	Burlington Resources Oil & Gas Company L	Bighorn 2-3	Gallatin	3	38 N	90 W	Wind River	Fremont	(1991)
42	49-013-22127	Burlington Resources Oil & Gas Company L	Bighorn 8-35	Madison	35	39 N	90 W	Wind River	Fremont	(2001)
43	49-013-05238	Carter Oil Company	Unit 1	Tensleep	32	38 N	93 W	Wind River	Fremont	(1950)
44	49-013-05354	Frexco Exploration Company	Frexco 1	Tensleep	28	32 N	91 W	Wind River	Fremont	(1958)
45	49-013-05475	BP America Production Company	USA-Cheney 1	Phosphoria	17	32 N	91 W	Wind River	Fremont	(1963)
46	49-013-05539	Davis Oil Company	Govt-Grieve 1	Morrison	34	33 N	91 W	Wind River	Fremont	(1958)
47	49-013-05631	Inspire State Oil	State 2	Tensleep	16	33 N	91 W	Wind River	Fremont	(1952)
48	49-013-05999	Edmiston Gladys	Govt 1	Cody	26	35 N	91 W	Wind River	Fremont	(1961)
49	49-013-06017	Conoco Inc.	Love Ranch 1	Mesaverde	11	35 N	91 W	Wind River	Fremont	(1960)
50	49-013-06068	Conoco Inc.	Squaw Butte Unit 14-4	Lance	14	36 N	91 W	Wind River	Fremont	(1960)
51	49-013-06175	Conoco Inc.	Unit 11-1	Fort Union	11	37 N	91 W	Wind River	Fremont	(1959)
52	49-013-06391	True Oil LLC	Garvin 1	Fort Union	14	38 N	91 W	Wind River	Fremont	(1959)
53	49-013-06440	Chevron USA Inc.	Hugh Day 1	Wind River	12	38 N	91 W	Wind River	Fremont	(1959)
54	49-013-06494	Atlantic Richfield Company	Lysite Unit 1	Cody	35	39 N	91 W	Wind River	Fremont	(1947)
55	49-013-06504	Gulf Oil Corporation	Federal W-73311 1	Lance	23	39 N	91 W	Wind River	Fremont	(1959)
56	49-013-05622	Morton & Caperton	Govt-Midland 1	Tensleep	13	33 N	90 W	Wind River	Fremont	(1962)
57	49-013-05889	Davis Oil Company	Govt 1	Muddy	30	34 N	89 W	Wind River	Fremont	(1958)
58	49-025-06038	Conoco Inc.	Squaw Butte Unit 23-3	Lance	23	36 N	89 W	Wind River	Natrona	(1960)
59	49-013-06169	Encana Oil and Gas USA Inc.	Graham Unit 1	Fort Union	21	37 N	89 W	Wind River	Fremont	(1961)
60	49-025-06484	Pure Oil	Unit 2-A	Cody	2	38 N	89 W	Wind River	Natrona	(1959)
61	49-025-06565	Union Oil Co. of California	Badwater Unit 1	Mesaverde	35	39 N	89 W	Wind River	Natrona	(1949)
62	49-029-21009	Hunt Energy Corporation	Loch Katrine Unit 1	Madison	2	51 N	100 W	Bighorn	Park	(1982)
63	49-029-21064	Gary-Williams Production Company	Emblem Bench 1R	Morrison	2	51 N	98 W	Bighorn	Park	(1991)
64	49-003-20379	Eastern Minerals Corporaton	Michaels Ranch Fee 17-15	Tensleep	17	51 N	96 W	Bighorn	Big Horn	(1996)
65	49-003-20597	BP America Production Company	Adams 1	Morrison	17	51 N	94 W	Bighorn	Big Horn	(1981)
66	49-003-20124	True Oil LLC	Rio Unit 33-20	Fuson	20	51 N	93 W	Bighorn	Big Horn	(1969)
67	49-029-20601	Gulf Energy Corporation	Buffalo Creek-Fed 1	Tensleep	32	48 N	99 W	Bighorn	Park	(1976)
68	49-029-20409	Bill Barrett Corporation	Sellers Draw Unit II 1	Phosphoria	21	48 N	99 W	Bighorn	Park	(1976)
69	49-043-20380	American Beryllium Oil Corp.	Ridge Unit 1-21	Dakota	21	48 N	97 W	Bighorn	Washakie	(1978)
70	49-003-20574	Devon Energy Production Company LP	Tatman Mtn. W-60980 1-20	Morrison	20	49 N	96 W	Bighorn	Big Horn	(1981)
71	49-003-20469	Southern Mineral Corporation	Schuster Flats 13355 26-1	Dakota	26	49 N	95 W	Bighorn	Big Horn	(1978)
72	49-003-20466	Devon Energy Production Company LP	Dobie Creek W-14076 1-11	Skull Creek	11	49 N	94 W	Bighorn	Big Horn	(1978)
73	49-003-05250	Stanolind Oil & Gas Company	Sykes Mobley 1	Muddy	25	50 N	93 W	Bighorn	Big Horn	(1955)

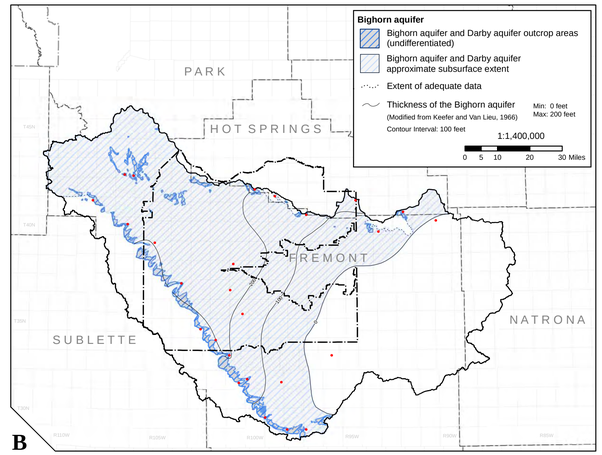
Plate VI. Geologic cross sections, Wind/Bighorn River Basin, Wyoming

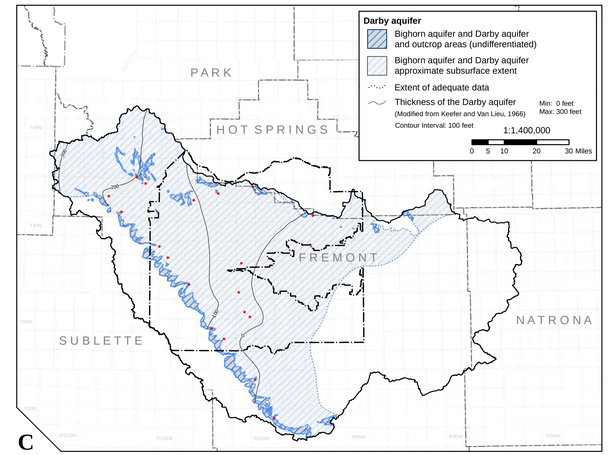
Compiled by
Scott Quillinan, James Rodgers, and David Copeland

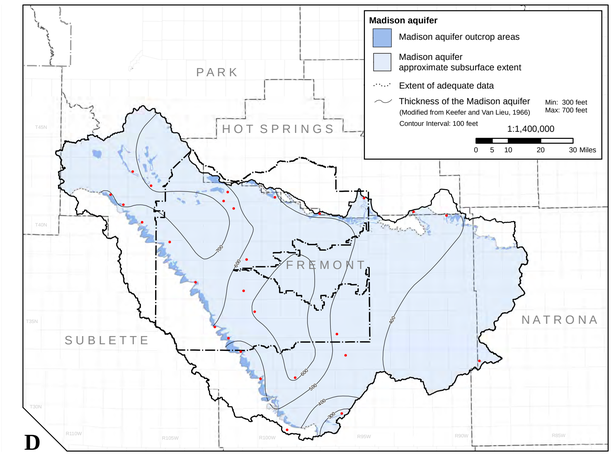
2012

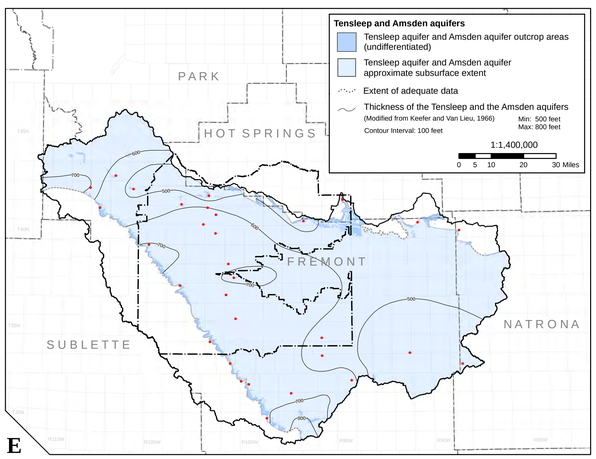
Scale 1:380,000
Vertical exaggeration ~ 2x
Lines of section on Plate I

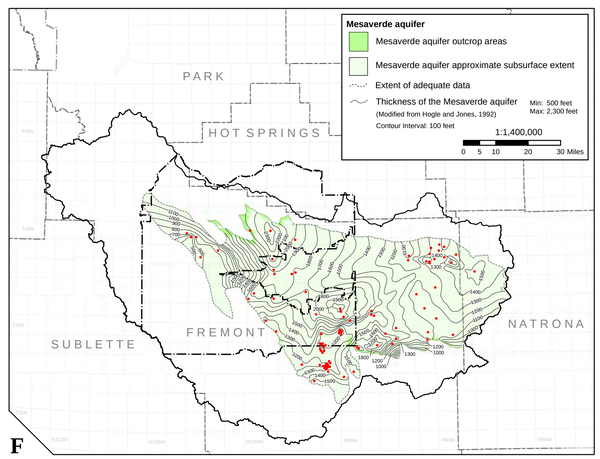


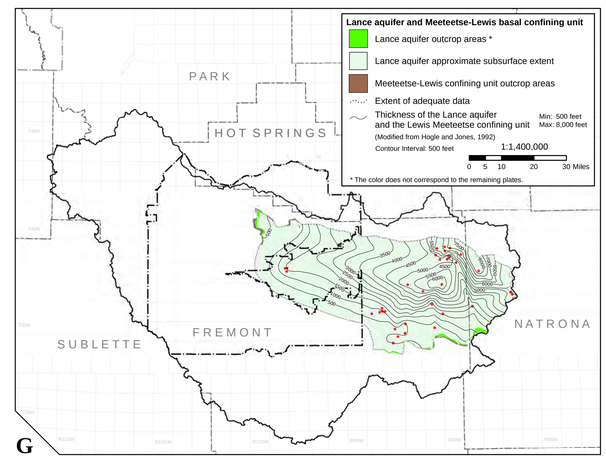


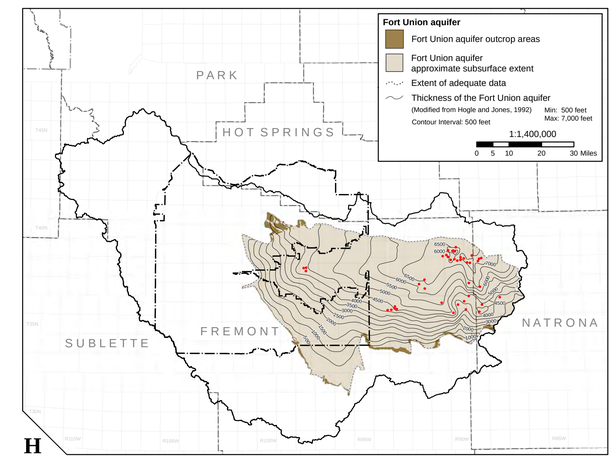


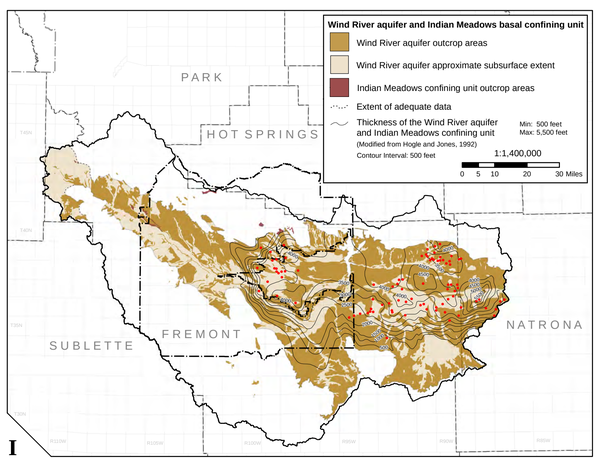












Explanation

- Well control
- Isopach (feet)
- Extent of adequate data
- County boundary
- State boundary
- Wind River drainage basin boundary
- Township and Range boundaries
- Wind River Indian Reservation Boundary

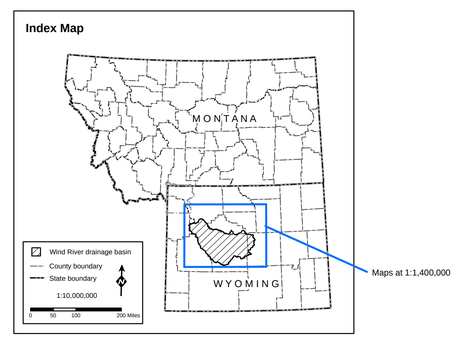


Plate VII. Isopach Maps of Selected Aquifers - Wind River Basin

compiled by

Scott Quillinan, Tomas Gracias, and David Copeland

2012

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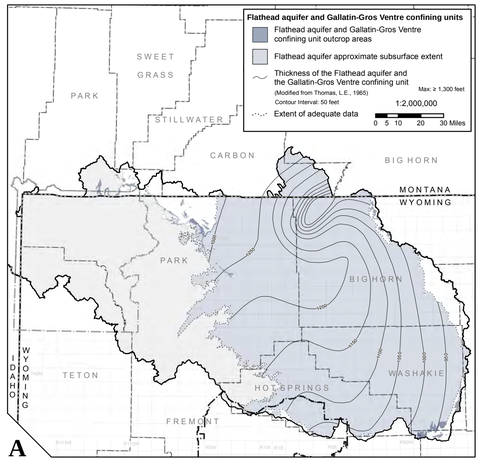

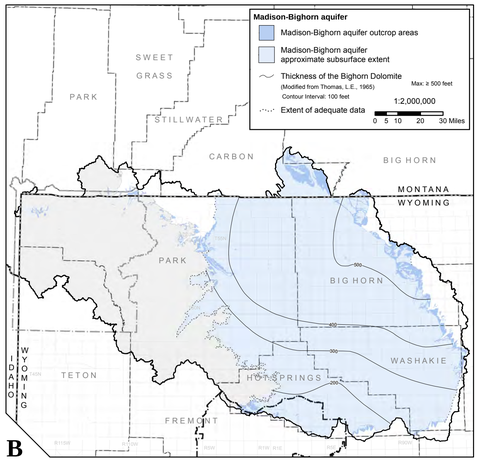

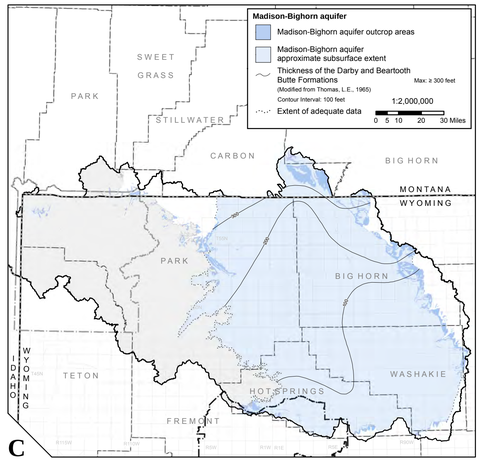

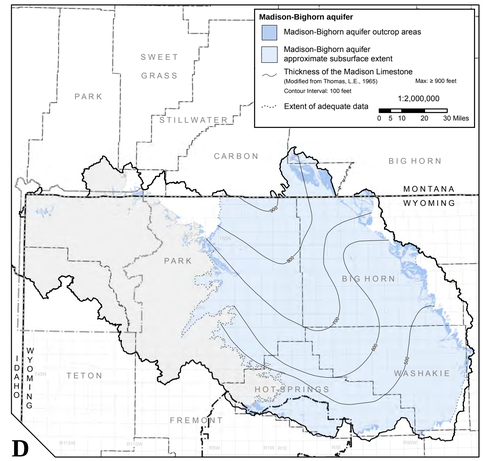

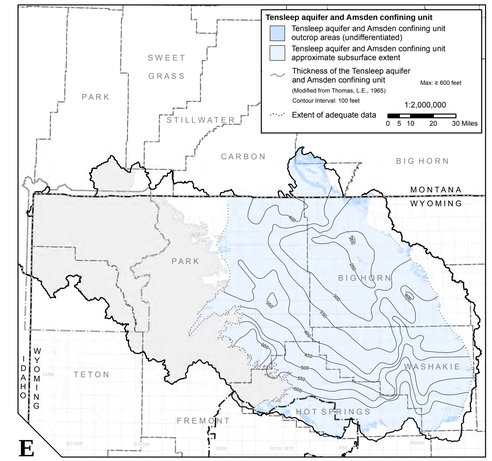

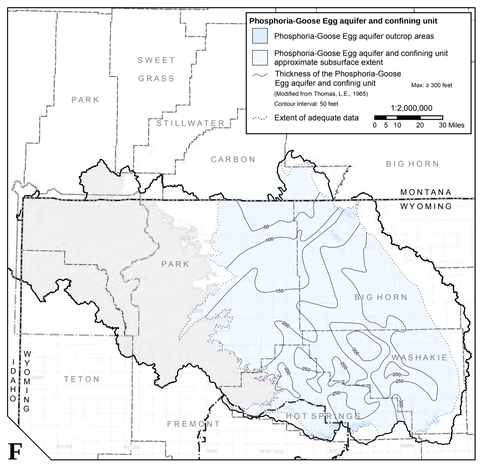

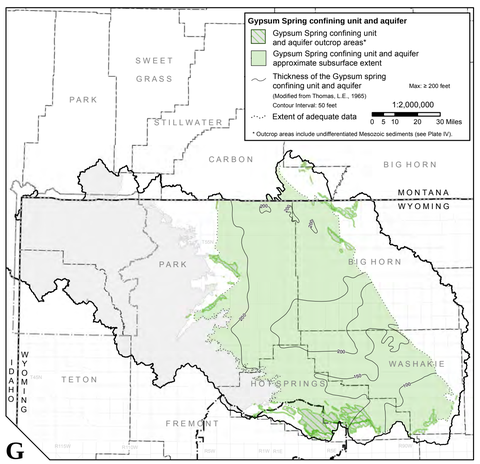

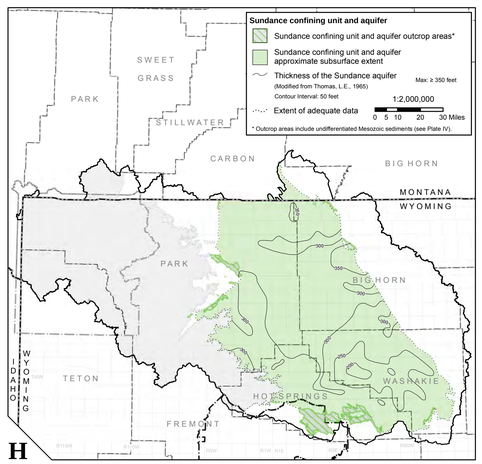

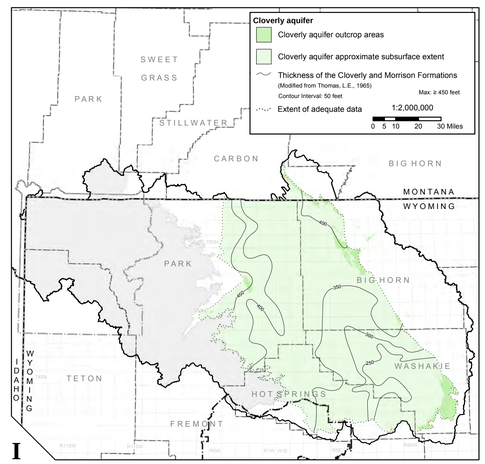

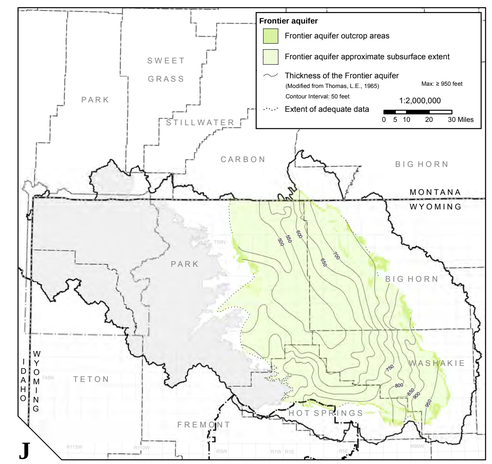

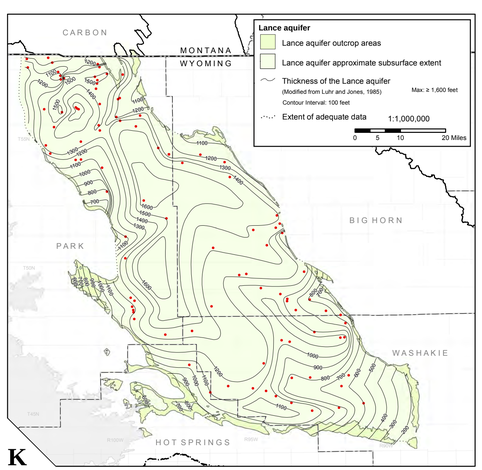

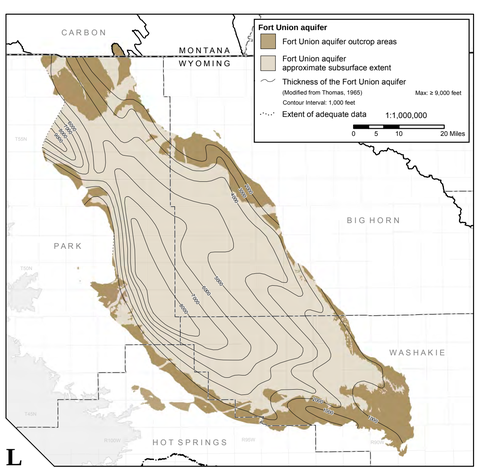

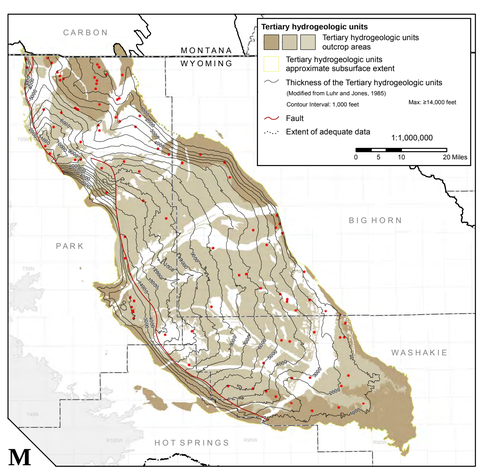

Explanation

- Well control
- Isopach (feet)
- Extent of adequate data
- Fault
- County boundary
- State boundary
- Bighorn River drainage basin boundary
- Township and Range boundaries
- Yellowstone National Park boundary
- Wind River Indian Reservation boundary
- Covered with volcanic rocks

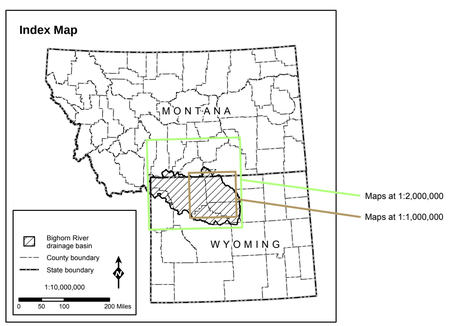

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Plate VIII. Isopach Maps of Selected Aquifers - Bighorn Basin

compiled by

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2012

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Region	U.S. Geological Survey National Water Information System (NWIS)						Other sources								All sources		Specific capacity		Transmissivity				Porosity		Hydraulic conductivity		Storativity/storage coefficient		Sources of data
	Well yield				Spring discharge		Well yield						Spring discharge		Well yield or spring discharge				Drill stem tests		All other tests								
	Flowing		Pumped		Flowing		Flowing		Pumped or unknown		Oil and gas well data		Flowing		Pumped or flowing														
	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range (median) (gal/min)	Count	Range [(gal/min)/ft]	Count	Range (ft²/day)	Count	Range (ft²/day)	Count	Range (percent)	Count	Range (ft/day)	Count	Range (unitless)	
Hydrogeologic units in Cenozoic lithostratigraphic units																													
Quaternary alluvial aquifers																													
WRB			86	0–200 (12)	1	10			90	0–1,010 (18)					177	0–1,010 (15)	156	0.12–140			70	9.6–124,000			11	6.2–2,500	4	0.0001–0.001	1, 13, 20, 30, 33, 39, 41, 45
BHB			43	0.5–1,400 (12)	1	1			53	4–600 (25)			1	5	98	0.5–1,400 (20)	45	0.22–200			42	0.1–10,700					14	0.003–0.2	1, 7–9, 13, 25, 29, 42, 51–54
AYV			2	2; 128					6	25–108 (30)			2	13.5; 44.9	10	2–128 (30)	6	3–39			2	469; 804							1, 11, 12, 25, 48
Aquifers in Quaternary lacustrine deposits																													
AYV									6	2–46 (33.5)					6	2–46 (33.5)	4	0.22–1.7			9*	6.7–8,140					5	0.0002–0.002	11, 16, 32
Aquifers in Quaternary landslide deposits																													
WRB					1	21									1	21													1
AYV					1	808									1	808													12, 48
Aquifers in Quaternary dune sand (eolian) deposits																													
WRB					1	27.5									1	27.5													1
Quaternary terrace-deposit aquifers																													
WRB			11	6–20 (8)	1	0.2			14	2–750 (19.5)					26	0.2–750 (16.5)	17	0.07–70			8	1,710–162,000			3	180–230	2	0.006; 0.02	1, 13, 20, 33, 37, 41, 43, 45
BHB			60	0.8–1,600 (12)					69	3–900 (20)			1	30	130	0.8–1,600 (16.8)	70	0.25–2,700			33	26.8–10,600							1, 7, 9, 25, 34, 36, 40, 42, 51, 52, 54
Quaternary glacial-deposit aquifers																													
WRB									4	15–20 (15)					4	15–20 (15)	4	0.75–20			2	2,010; 4,020							13, 41
BHB			4	4–7 (5)					1	11					5	4–11 (5)	3	0.07–0.44			1	67							1, 25
AYV			1	50					5	5–20 (9)			2	1.3; 36	8	1.3–50 (12.5)	4	3.3–53											1, 10–12, 48
Aquifers in rhyolite flows, tuff, and intrusive igneous rocks																													
AYV					1	16									1	16													10
White River aquifer																													
WRB					2	1; 2									2	1; 2													1
Aycross–Wagon Bed confining unit (all measurements from Wagon Bed Formation)																													
WRB			1	2	3	0.5–5 (1)									4	0.5–5 (1.5)													1
Quaternary and Tertiary volcanic-rock aquifers																													
AYV					7	0.5–37 (1.5)									7	0.5–37 (1.5)													1, 13
Wind River aquifer																													
WRB	8	0.1–50 (2)	367	0–350 (12)	2	2;2			206	1–400 (20)	3	1–7 (1)			586	0–400 (15)	422	0.004–400	2*	0.05–3.1	59	0.05–2,140	4*	3–20			10	0.0001–0.002	1, 5, 13, 24, 33, 41, 44, 46
Willwood aquifer																													
BHB	2	3;3	40	2–1,100 (8)					68	1–60 (6.5)					110	1–1,100 (7.8)	84	0.004–8.5			2	7.2; 9.9					2	0.4;0.4	1, 7, 25, 29, 40, 42, 54
AYV			1	100											1	100	1	20											1
Fort Union aquifer																													
WRB			2	1; 10							10	1–10 (2)			12	1–10 (2)	1	0.1											1, 13, 41
BHB			14	4–30 (10)	1	2	1	0.25	12	3–40 (5.5)					28	0.2–40 (6.5)	21	0.01–3											1, 7, 25, 54
Hydrogeologic units in Mesozoic lithostratigraphic units																													
Lance aquifer																													
WRB			1	10							4	1–7 (5)			5	1–10 (5)			1*	2.2			2*	15–20					1, 13, 41
BHB			6	6–84 (37.5)					2	10;10					8	6–84 (20)	6	0.17–25	2	4.2;17.9	2	31.5;55.9					1	0.0004	1, 25, 54, 55
Meeteetse aquifer and confining unit																													
BHB	1	3.5	5	4–500 (10)	1	5									7	3.5–500 (10)	1	0.4											1, 54
Mesaverde aquifer																													
WRB	1	1	2	7; 20					2	10; 15	8	1–350 (5)			13	1–350 (7)	2	0.03; 7.5	1*	3.9	2	8.0; 2,010	1*	18					1, 41
BHB	1	25	15	5–50 (13)	2	8; 9.5			9	1–25 (10)					27	1–50 (10)	11	0.05–3.8	2	1.1; 1.3									1, 7, 51, 52, 54
Cody confining unit																													
WRB			11	4–20 (9)					13	1.5–20 (8)	14	1–20 (2)			38	1–20 (6.5)	19	0.01–4	4*	1.6–3.2	9	2.7–1,070	2*	15–18					1, 13, 41
BHB	2	4; 7.1	3	12–25 (20)					4	1–20 (6)					9	1–25 (7.1)	7	0.01–1.2			1	121							1, 25, 54
Frontier aquifer																													
WRB	1	4	9	1.5–40 (6)	4	2.5–38 (4)	2	2;2	19	0.5–120 (10)	1	10			35	0.5–120 (6)	26	0.003–25	20*	0.2–39.6	14	0.8–6,700	15*	10–25					1, 13, 30, 41
BHB	7	1–9 (2.7)	11	4–40 (15)	2	0.6; 9	1	50	27	1–200 (16)	27	0.2–14.1 (1.3)			75	0.2–200 (5)	15	0.01–8.7	147*	0–53.6			125*	6–26					1, 3, 7, 9, 13, 25, 47, 51, 52, 54
AYV			1	18											1	18													1
Mowry confining unit																													
WRB					1	2									1	2													1
BHB	1	5			4	0.01–100 (0.8)									5	0.01–100 (1.5)													1
Muddy Sandstone aquifer																													
WRB																			6*	0.04–0.7			4*	7–18					41
BHB			3	1–20 (8)					8	1–43 (3.5)	1	14			12	1–43 (6)			6	0.08–5.9									1, 51, 52, 54
Thermopolis confining unit																													
WRB			1	10											1	10	1	0.1											1
BHB			2	10; 15	2	3; 5			2	1; 27					6	1–27 (7.5)	1	0.06	1	4.0									1, 54
Cloverly aquifer																													
WRB			9	10–230 (77)					6	5–20 (13.5)	3	1–3 (2)			18	1–230 (20)	13	0.13–4.3	10*	2.4–78.2			7*	15–25					1, 13, 41
BHB	1	8	4	4–60 (20.5)	2	4; 16			4	12–26 (17)	5	1.2–10.4 (4.2)			16	1.2–60 (11.2)	4	0.02–1.5	10*	0.1–7.3			9*	7–15					1, 13, 25, 47, 51, 52, 54
Morrison confining unit (WRB) and Morrison confining unit and aquifer (BHB)																													
WRB			1	6											1	6	1	0.04	4*	0.04–0.4			2*	10					1, 41
BHB			1	2							3	0.2–3.4 (1.5)			4	0.2–3.4 (1.8)			3	0.1–0.6			1	15					1, 25, 51, 52
Sundance aquifer (WRB) and Sundance confining unit and aquifer (BHB)																													
WRB			1	15	1	6									2	6; 15	1	3.8											1, 13
BHB											5	0.8–35.1 (1.3)			5	0.8–35.1 (1.3)			5	0.07–2.2									51, 52
Gypsum Spring confining unit (WRB) and Gypsum Spring confining unit and aquifer (BHB)																													
WRB					3	5–28 (12)									3	5–28 (12)													1, 13
BHB			1	20	3	4–50 (8)			1	27					5	4–50 (20)	1	20	1	4.0									1, 54
Nugget aquifer																													
WRB			3	10–90 (90)	1	5			3	20–28 (28)	4	1–10 (3.5)			11	1–90 (10)	6	0.8–14	4*	0.06–31.8			3*	10–20					1, 13, 30, 41
Chugwater aquifer																													
WRB			2	2; 9	5	5–75 (50)			3	15–20 (18)	2	10;10			12	2–75 (16.5)	4	0.56–4.5	6*	0.05–15.9			4*	10–15					1, 13, 41
BHB	1	6	6	1–11 (7.5)	5	1–150 (6)	1	200	3	8–25 (20)	1	0.1			17	0.1–200 (8)	4	0.7–17	5*	0.7–5.9			6*	15–22					1, 9, 13, 21a, 21b, 25, 51, 52
Dinwoody confining unit																													
WRB																			2*	0.05–1.1			1*	15					41
Goose Egg aquifer and confining unit																													
BHB	2	2; 5			1	40	1	60					1	4,500	5	2–4,500 (40)													1, 6, 21a, 21b
Hydrogeologic units in Paleozoic and Precambrian lithostratigraphic units																													
Phosphoria aquifer and confining unit																													
WRB	1	1.2	4	3–900 (77.5)	6	1–280 (58.8)	1	5	1	1	30	1–120 (5)			43	1–900 (5)	1	3.3	26*	0.05–8.6			19*	10–24					1, 13, 21a, 21b, 41, 57
BHB			1	0.5			5	5–583 (7.5)	6	5–67.5 (10)	25	0.1–27.5 (1.2)			37	0.1–583 (2)	1	5.5	44*	0.01–12.9	1	53.6	31*	2–24			1	0.0002	1, 2, 18, 21a, 21b, 25, 47, 49, 51, 52, 54
Tensleep aquifer																													
WRB	4	13.6–150 (70.6)	5	120–625 (364)	2	25; 332	8	20–250 (162)	5	10–215 (18)	22	2–200 (22.5)			46	2–625 (67.5)	12	0.43–310	22*	0.05–84.8	8	305–26,800	14*	5–32	1	2			1, 13, 30, 41, 57, 61
BHB	16	5–250 (20)	7	1–181 (8)	3	5–1,410 (353)	15	2–1,000 (50)	21	2–50.5 (11)	124	0.2–44 (6.4)	4	449–1,000 (900)	190	0.2–1,410 (9.5)	9	0.4–15	168*	0.01–176	9	0.01–6,700	35*	3.3–26	1	0.01			1, 2, 4, 6, 9, 17–19, 21a, 21b, 22, 25, 27, 31, 51, 52, 54, 56
Amsden aquifer (WRB) and Amsden confining unit (BHB)																													
WRB																			2*	0.1–4.9			1*	11					41
BHB	1	52					3	10–52 (50)	1	14	5	0.8–3.6 (2.3)	1	3,060	11	0.8–3,060 (10)	2	0.2	4	0.1–0.7			2*	7–10					1, 21a, 21b, 25, 27, 31, 51, 52
Madison aquifer																													
WRB	3	10–500 (262)	2	130; 700	5	7–94 (20)	5	25–900 (110)	8	15–300 (108)	2	1; 2			25	1–900 (90)	10	0.06–300	2*	0.1; 1.2	16	12.3–80,400	2	12; 15					1, 13, 23, 30, 41, 43, 57, 58, 61
BHB	11	15–1,100 (380)	4	5–1,650 (168)			20	21–6,000 (312)	23	3–730 (56)	38	0.6–61.9 (14.6)	2	2,960; 9,470	98	0.6–9,470 (39.6)	21	0.02–20	37*	0.8–429	17	83.1–5,490	8*	1.5–26	2	0.08; 2.7	3	0.00002–0.001	1, 6, 14, 15, 19, 21a, 21b, 22, 25–28, 31, 35, 38, 50–52, 54, 56, 59, 60
AYV					2	4,490; 8,530									2	4,490; 8,530													12, 48
Darby aquifer (all measurements from Jefferson Formation)																													
BHB									1	23	1	8.1			2	8.1; 23			2	13.4; 590									19, 51, 52, 54
Bighorn aquifer																													
WRB					3	0.2–628 (5)			2	25;25					5	0.2–628 (25)	2	2.5; 4.2			2	670; 1,110							1, 13, 41
BHB			1	323	6	1–22 (3)			2	42; 94	2	4; 11.3	1	3,050	12	1–3,050 (8.6)	1	1.1	4*	4.3–268			3*	2–25					1, 19, 21a, 21b, 22, 25, 51, 52, 54
Gallatin confining unit																													
WRB			1	8					1	26					2	8; 26													1, 13, 57
BHB									2	1; 9	1	11.8			3	1–11.8 (9)			1	5.7									51, 52, 54
Gros Ventre confining unit																													
BHB			1	110	2	3;3									3	3–110 (3)													1
Flathead aquifer																													
WRB					2	31; 85									2	31; 85													1, 13
BHB	2	105; 531			3	7.5–15 (15)			1	96					6	7.5–531 (55.5)			2	26.8; 30.8			1*	25					1, 19, 22, 54
Precambrian basal confining unit																													
WRB					2	1.1; 8									2	1.1; 8													1, 13
BHB			5	1–20 (8)	1	10									6	1–20 (9)	5	0.02–2.8											1

[gal/min, gallons per minute; (gal/min)/ft, gallons per minute/foot of drawdown; ft²/day, feet squared per day; ft/day. feet per day; WRB, Wind River Basin; BHB, Bighorn Basin; AYV, Absaroka Range and Yellowstone volcanic area]

*Values reported as range or average in original source so count cannot be determined.

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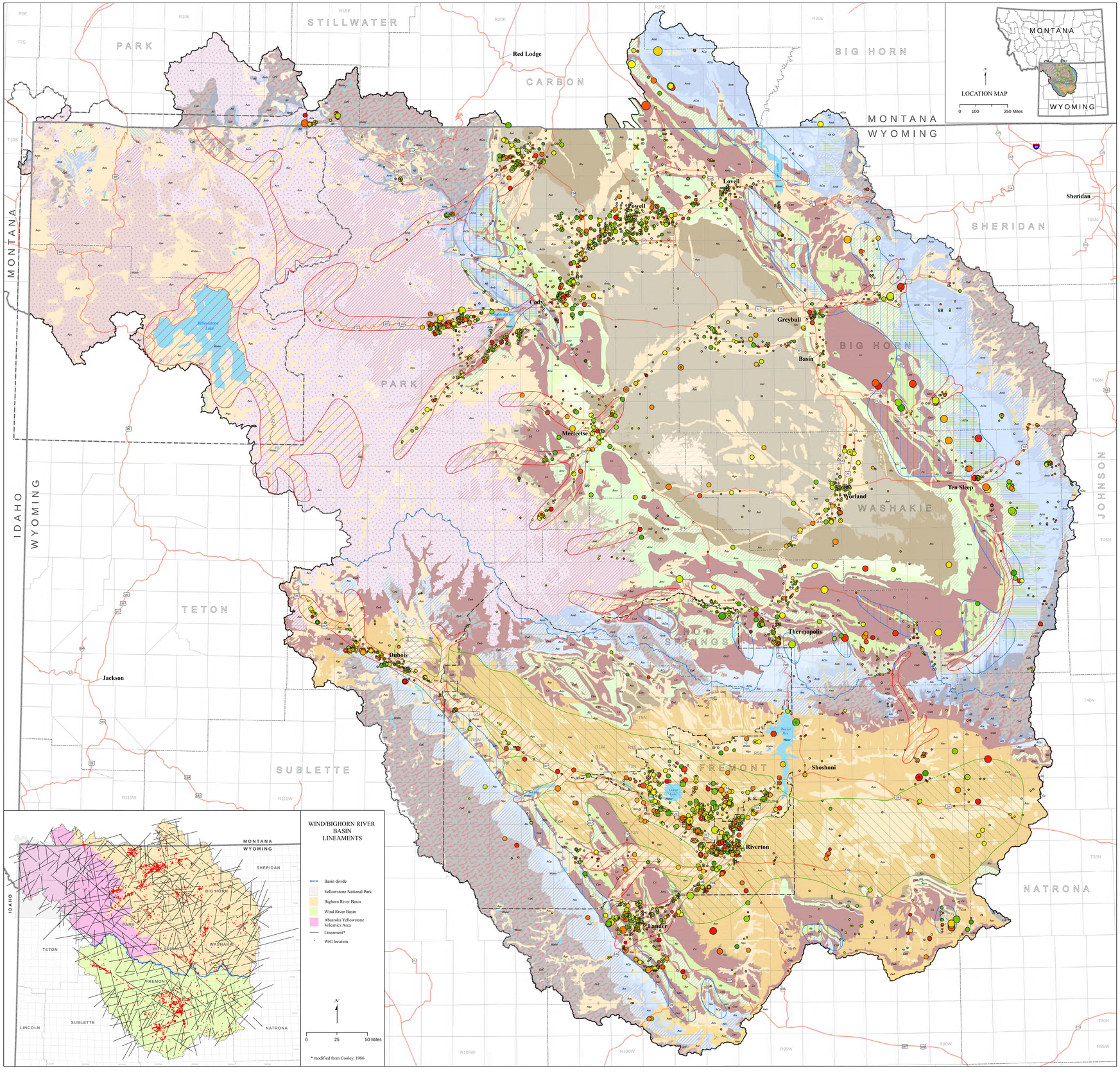
Plate IX. Summaries of well yield, spring discharge, and hydraulic properties, Wind River and Bighorn Basins, Absaroka Range and Yellowstone volcanic area, Wyoming.



Surface Hydrogeology
Wind/Bighorn River Basin

with
Wyoming State Engineer's Office Permitted and Completed Wells 2000-2009

compiled
by
Nikolaus Gribb, Scott Quillinan, Brett Worman
Tomas Gracias, and Tim Bartos

2012

0 5 10 20 30 Miles

Scale 1:380,000
1 inch equals approximately 6 miles

Explanation

- Interstate highway
- US highway
- State highway
- State boundary
- County boundary
- Township and Range boundaries
- Wind River Indian Reservation boundary
- Yellowstone National Park boundary
- Wind River/Bighorn River Basin hydrologic divide

Well depth (ft)
- 0 - 50
- 51 - 100
- 101 - 500
- 501 - 1,000
- > 1,000

Well yield (gpm)
- 0 - 25
- 26 - 100
- 101 - 500
- 501 - 1,000
- > 1,000

Potential Development Areas from BRS, Inc. et al. (2003)
- Alluvial
- Tertiary
- Paleozoic

Surface Hydrogeology

(See **Plates II, III, and V** for geologic unit correlations.)

Bighorn River Basin and Absaroka-Yellowstone Volcanics Hydrogeologic Units

CENOZOIC
- Water
- Aqu — Quaternary unconsolidated deposit aquifers
- Undefined volcanic hydrogeologic units
- Undefined Tertiary hydrologic units
- Ayr — Yellowstone Group aquifer
- Aav — Absaroka Volcanic Supergroup aquifer
- Awh — White River aquifer
- Cwb — Wagon Bed confining unit
- Awf — Willwood aquifer
- Afu — Fort Union aquifer

MESOZOIC

Lower Tertiary/Upper Cretaceous aquifer system
- Undefined Mesozoic hydrologic units
- Ala — Lance aquifer
- Ame — Meeteetse aquifer and confining unit
- Amv — Mesaverde aquifer

Lower and middle Mesozoic aquifers and confining units
- Cc — Cody confining unit
- Aft — Frontier aquifer
- Cmt — Mowry–Thermopolis confining unit
- Undifferentiated Mesozoic geologic units (May include: Mowry–Thermopolis c.u., Muddy Sandstone aq., Cloverly aq., Morrison c.u. and aq., Sundance c.u. and aq., Gypsum Spring c.u. and aq., Nugget aq.)
- Cwd — Chugwater–Dinwoody aquifer and confining unit
- Undifferentiated Mesozoic Paleozoic geologic units

PALEOZOIC
- Undifferentiated Paleozoic geologic units (May include: Goose Egg–Phosphoria aq. and c.u., Amsden c.u., Madison–Bighorn aq., Gallatin–Gros Ventre c.u.)

Paleozoic aquifer system
- ACp — Goose Egg–Phosphoria aquifer and confining unit
- ACte — Tensleep aquifer and Amsden confining unit
- Amb — Madison–Bighorn aquifer
- Afl — Gallatin–Gros Ventre confining unit and Flathead aquifer

PRECAMBRIAN
- CpC — Precambrian basal confining unit

Wind River Basin Hydrogeologic Units

CENOZOIC
- Glacial ice
- Water
- Aqu — Quaternary unconsolidated deposit aquifers
- Undefined volcanic hydrogeologic units
- Asr — Split Rock aquifer
- Awh — White River aquifer
- Apr — Absaroka Volcanic Supergroup aquifer
- Cwb — Aycross–Wagon Bed confining unit
- Undifferentiated Tertiary geologic units (May include Aycross–Wagon Bed c.u., Wind River aq.)
- Awr — Wind River aquifer
- Cm — Indian Meadows confining unit

Fort Union–Lance aquifer
- Afu — Fort Union aquifer

MESOZOIC
- Ala — Lance aquifer
- Cml — Meeteetse–Lewis confining unit
- Amv — Mesaverde aquifer
- Cc — Cody confining unit

Lower and middle Mesozoic aquifers and confining units
- Aft — Frontier aquifer
- Undifferentiated Mesozoic geologic units (May include: Frontier aq., Mowry–Thermopolis c.u., Muddy Sandstone aq., Cloverly aq., Morrison c.u., Sundance–Nugget aq., Gypsum Spring c.u.)
- Cmt — Mowry–Thermopolis confining unit
- Asn — Sundance–Nugget aquifer
- Cwd — Chugwater–Dinwoody aquifer and confining unit

PALEOZOIC
- ACp — Goose Egg–Phosphoria aquifer and confining unit
- Undifferentiated Mesozoic/Paleozoic geologic units

Paleozoic aquifer system
- Ata — Tensleep and Amsden aquifers
- Undifferentiated Paleozoic geologic units (May include: Madison aq., Darby aq., Bighorn aq., Gallatin–Gros Ventre c.u.)
- Amb — Bighorn aquifer
- Afl — Gallatin–Gros Ventre confining unit and Flathead aquifer

PRECAMBRIAN
- CpC — Precambrian basal confining unit

Disclaimer

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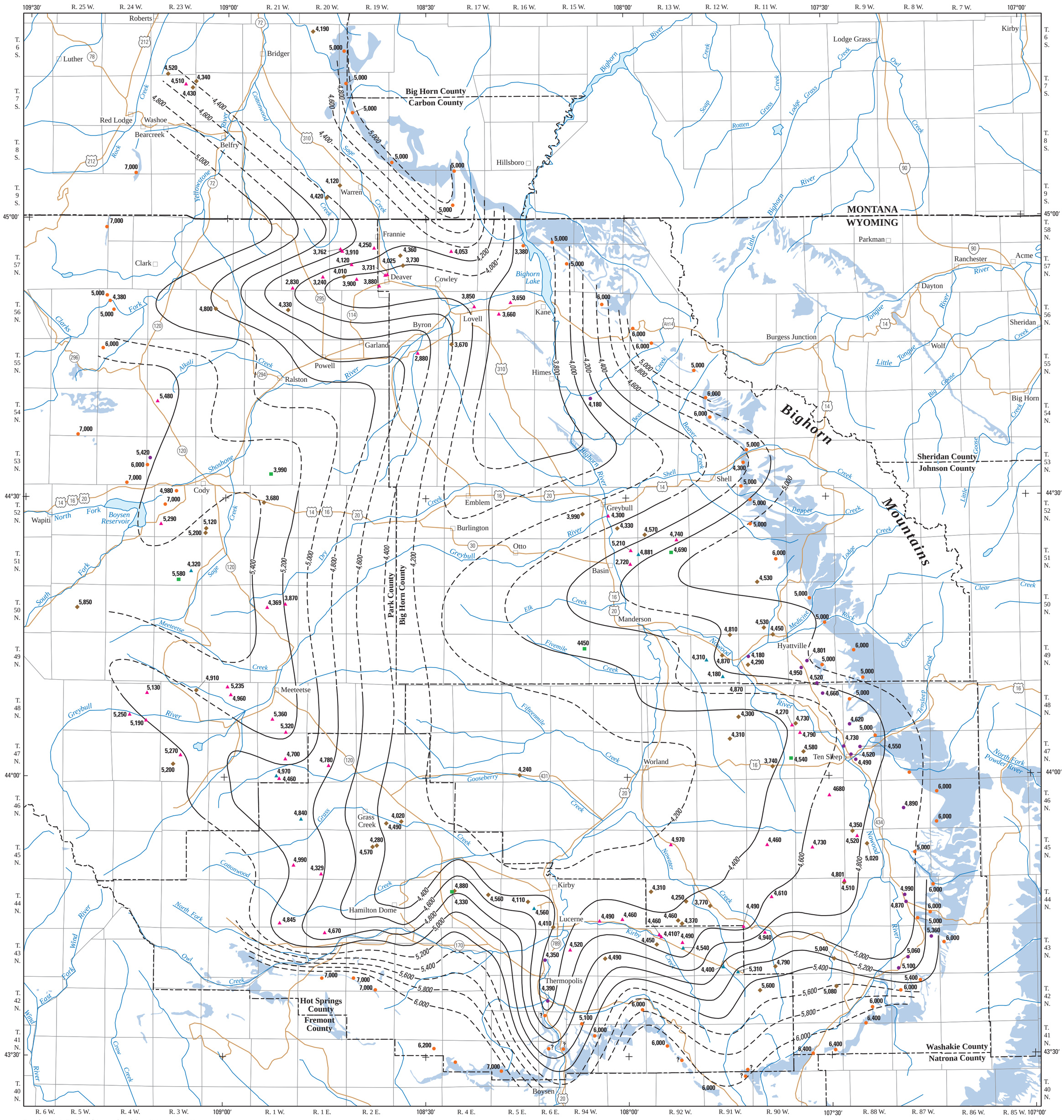
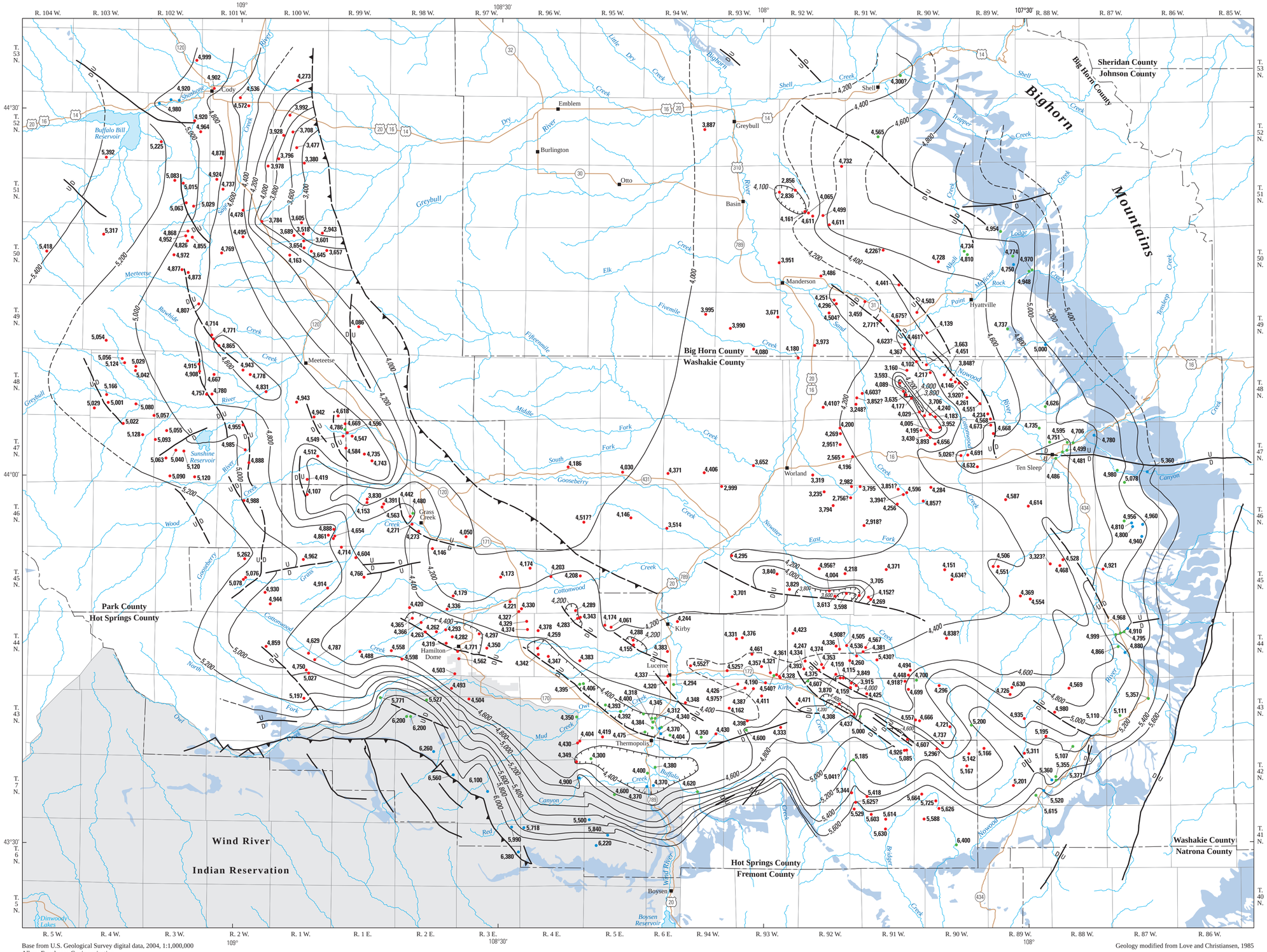
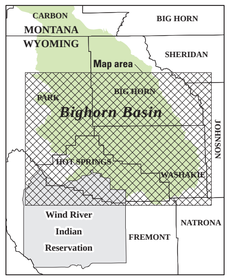


Plate XII. Predevelopment potentiometric surface of the Tensleep aquifer in the Bighorn Basin, west-central Wyoming (modified from Bredehoeft and Bennett, 1972)





Index map

EXPLANATION

Tensleep–Amsden Formation

5,600 — **Potentiometric contour and altitude of potentiometric surface,** in feet above sea level. Contour interval 200 feet. Dashed where inferred. Hachured areas indicate depressions. Correct representations of potentiometric depressions are shown where map scale permits. Lowest drawdown labeled otherwise

U/D — **Surface fault** — U, upthrown side; D, downthrown side

U/D — **Subsurface fault** — U, upthrown side; D, downthrown side

Thrust fault — line indicates where the fault intersects an unconformity between faulted strata below and unfaulted strata above; in other places, it indicates where the shallower part of the fault disappears into bedding planes. Sawteeth on upper plate. Some thrust faults are deeply buried and are approximately located on the basis of seismic data and drilling

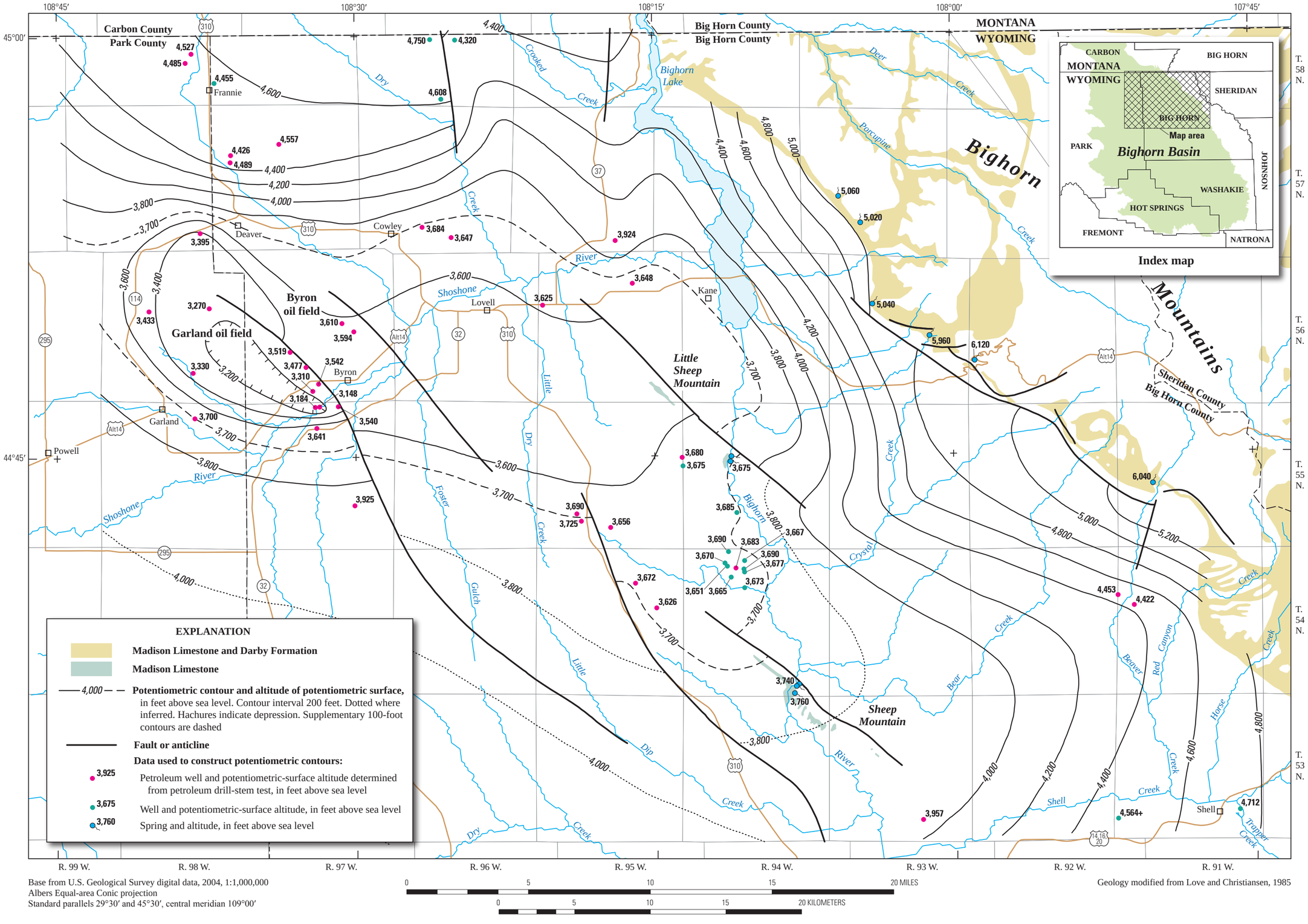
Data used to construct potentiometric contours:

5,520 Petroleum well and potentiometric-surface altitude, in feet above sea level as determined from oil-field pressure test. Queried where anomalous

5,615 Water well and potentiometric-surface altitude, in feet above sea level as determined from well-head pressure or physical measurement

4,940 Spring and potentiometric-surface altitude, in feet above sea level

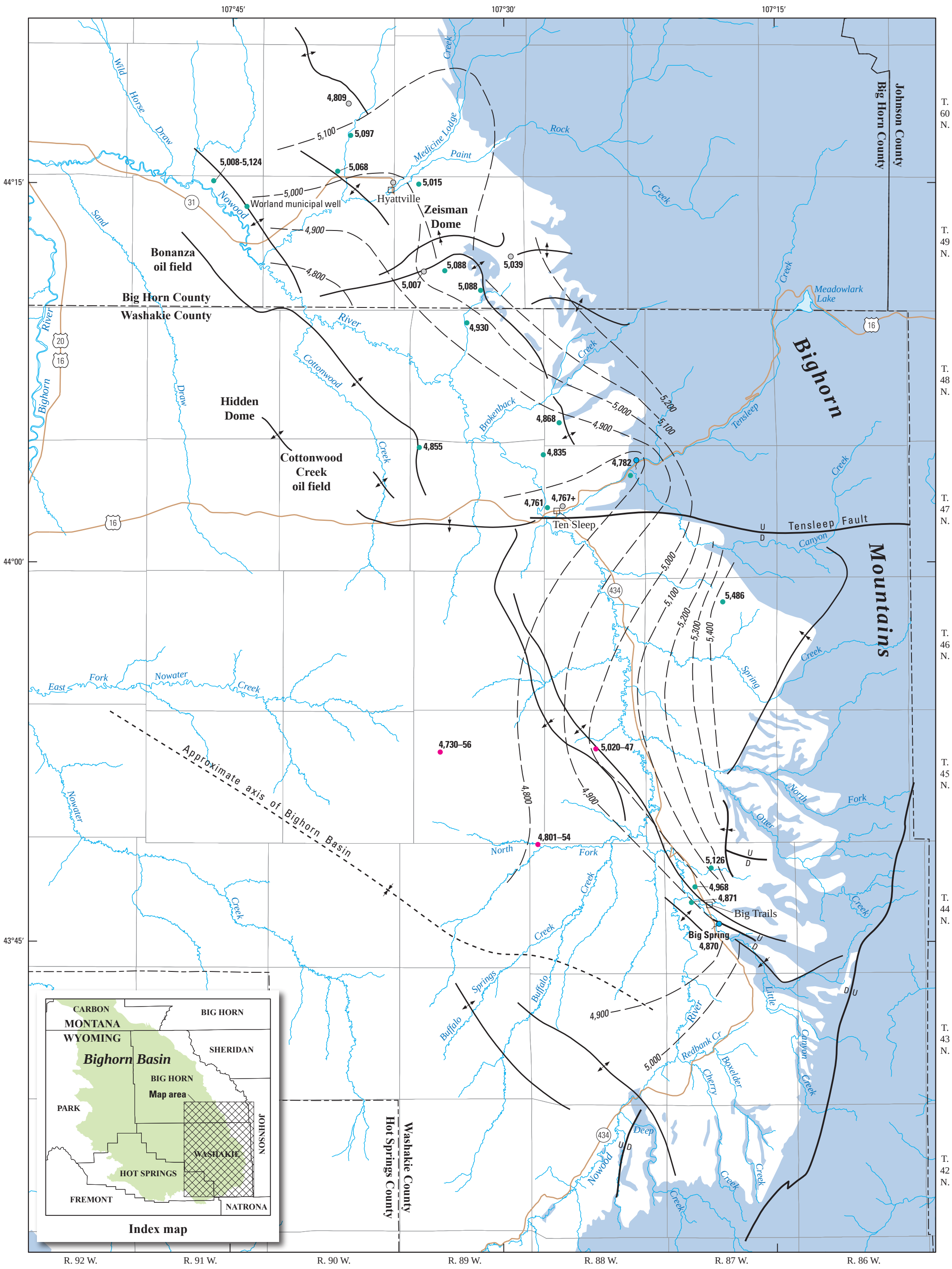
Plate XIII. Potentiometric surface of the upper part of the Paleozoic aquifer system (Tensleep aquifer and Goose Egg-Phosphoria aquifer and confining unit) in the southern Bighorn Basin, Wyoming (modified from Spencer, 1986a, plate 4, and Jarvis, 1986a, plate 4)



Base from U.S. Geological Survey digital data, 2004, 1:1,000,000
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′, central meridian 109°00′

Geology modified from Love and Christiansen, 1985

Plate XIV. Potentiometric surface of the Madison-Bighorn aquifer in the northeastern Bighorn Basin, Wyoming (modified from Doremus, 1986, fig. 13)



Base from U.S. Census Bureau digital data, 2001, 1:100,000
Transportation data from Federal Highway Administration, 2002, 1:100,000
Public land survey system data from U.S. Bureau of Land Management, 2007, 1:24,000
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′, central meridian 107°30′
North American Datum of 1983 (NAD 83)

0 5 10 15 MILES

0 5 10 15 KILOMETERS

Geology modified from Love and Christiansen, 1985

EXPLANATION

Rocks younger than Tensleep Sandstone

Tensleep Sandstone and older rocks

5,000 **Potentiometric contour** – Shows altitude at which water level would have stood in tightly cased wells, 1978. Dashed where inferred. Contour interval 100 feet. Datum is sea level

U D **Fault** – D, downthrown side; U, upthrown side

Anticline – Showing trace of axial plane and direction of plunge

Syncline – Showing trace of axial plane and direction of plunge

Monocline – Showing trace of axial plane

Data used to construct potentiometric contours:

4,801–54 Oil-test well and potentiometric-surface altitude, in feet above sea level

4,767+ Well completed in Madison–Bighorn aquifer and potentiometric-surface altitude, in feet above sea level

4,871 Well completed in Tensleep aquifer and Madison–Bighorn aquifer or Amsden aquifer or both and potentiometric-surface altitude, in feet above sea level

4,870 Spring and altitude, in feet above sea level

Plate XV. Potentiometric surface of the Madison–Bighorn aquifer, Ten Sleep area of the Bighorn Basin, Wyoming (modified from Cooley, 1986, plate 4)

Interpreting the past – providing for the future