WYOMING STATE GEOLOGICAL SURVEY

Erin A. Campbell, Director and State Geologist

Powder/Tongue/Northeast River Basins Water Plan Update
Groundwater Study
Level I (2002–2016)

Available Groundwater Determination
Technical Memorandum No. 8

by

Karl G. Taboga, Timothy T. Bartos, Laura L. Hallberg, Melanie L. Clark,
James E. Stafford, and Andrea M. Loveland

Prepared for the Wyoming Water Development Commission

Director and State Geologist Erin A. Campbell

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Front cover photos: (top) Cheyenne River near Mule Creek Junction, looking west from the bridge at Highway 85, (middle) Tongue River, looking west from the Welch Ranch Recreation Area near Acme, and (bottom) Powder River, looking north, from the Highway 14/16 bridge near Arvada.

Back cover photos: (top) Little Powder River near Weston Wyoming. Public domain photo by USGS, (middle) Little Bighorn River in Sheridan County, Wyoming. Photo by Wyoming Game and Fish Department,used with permission, and (bottom) Redwater Creek in the Belle Fourche River Basin, near Beaulah, Wyoming.

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December 2019

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Alec Osthoff, Editor

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

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Chapter 1

Introduction

Karl G. Taboga

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

The development of the present State Water Planning Process began in 1997 when the state legislature directed WWDC to conduct a feasibility study in collaboration with the University of Wyoming (UW) and the SEO. The study included public input and compilation of a statewide water inventory. Based on the feasibility study, the Wyoming Legislature accepted the recommended planning framework to update the original 1973 State Framework Water Plan, funding the State Water Planning Process in 1999, and providing funding 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
- direct water resource planning for the state of Wyoming for a 30-year timeframe

The Wyoming Framework Water Plan was completed between 2001 and 2006 (WWC Engineering and others, 2007), and summarized the separate water plans for Wyoming's seven major river basins (fig. 1-1).

Technical memoranda in the previous Powder/Tongue River Basin Water Plan (HKM Engineering and others, 2002a) and Northeast Wyoming River Basin Water Plan (HKM Engineering and others, 2002b) contain groundwater resource investigations that thoroughly examine the basins' resources and usage (see Technical Memorandum N in both reports). This Available Groundwater Determination represents the most current assessment of the groundwater resources in the Powder/Tongue and Northeast River basins, updating and expanding the information presented in the 2002 groundwater investigations. The data contained in this memorandum are a compilation of existing information obtained by several state and federal agencies. While original maps and tables were developed, and existing maps and tables were updated and modified, no original research was conducted for this memorandum.

The format of this update follows the general layout of other recent groundwater determinations co-authored by the Wyoming State Geological Survey (WSGS) and U.S. Geological Survey (USGS) for the Green River Basin (2010), the Wind/Bighorn River Basin (2012), the Platte River Basin (2013), the Bear River Basin (2014), and the Snake/Salt River Basin (2014). This memorandum incorporates much of the content of these five previous studies, frequently without citation. Previous water plans are available on the WWDC website at: http://waterplan.state.wy.us/.

1.1 INTERAGENCY AGREEMENT AND SCOPE

The WWDC and WSGS entered into an Interagency Agreement in July 2015 to update the groundwater information contained in the previous Powder/Tongue River Basin Water Plan (HKM Engineering and others, 2002a) and Northeast Wyoming River Basin Water Plan (HKM Engineering and others, 2002b). The two agencies agreed to consolidate groundwater information for the two river basin plans into one large report, henceforth referred to as the Northeast River Basins (NERB) Plan. The geographical area covered by this report encompasses the northeast quarter of Wyoming and includes the drainages of the Little Bighorn, Tongue, Powder, Little Powder, Belle Fourche, Little Missouri, Cheyenne, and Upper Niobrara rivers. The agreement outlines the following tasks to update the previous water plans:

- Identify the major (i.e., most widely used) aquifers in the Northeast River Basins:
    - The USGS identified aquifers and confining units in a hydrostratigraphic nomenclature chart (fig. 7-8). Based on these analyses, the geologic units mapped on plate 1 and described in appendix A were organized into a comprehensive hydrostratigraphic chart and surface hydrogeology map for the NERB (pl. 2). In some cases, two or more minor aquifers that are hydrologically connected are grouped and treated as a single combined hydrogeologic unit. The general geology of the Northeast River Basins is discussed in chapter 4, and individual aquifers are detailed in chapter 7.

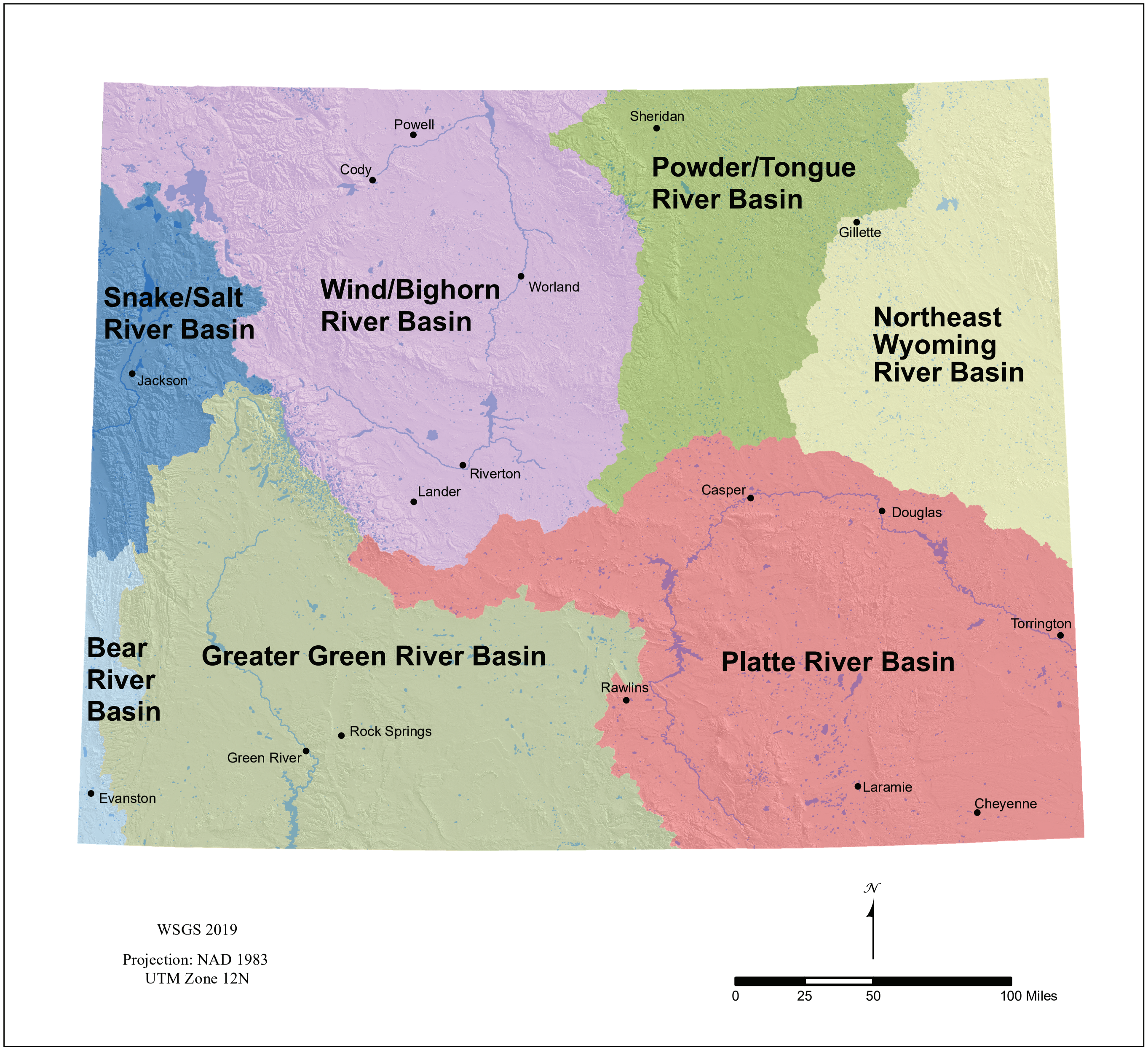

Figure 1-1. Major drainage basins, Wyoming.

- Define the three-dimensional extent of the aquifers:
    - Plate 2 is a map of the outcrop areas for the Northeast River Basins' aquifers and confining units. Nine cross sections (figs. 4-3 through 4-11) illustrate the subsurface configuration of the geologic units that constitute the hydrogeologic units at selected locales within the NERB.
- Describe the following hydraulic, hydrogeologic, and hydrogeochemical properties of the aquifers and confining units:
    - Physical characteristics— chapters 4 and 7 discuss the lithologic and hydrogeologic characteristics of the hydrogeologic units identified in plate 2.
    - Water chemistry with comparisons to applicable state and federal regulatory standards by class of use—chapters 5 and 7 contain extensive discussions of basin water quality with comparisons to regulatory standards. Statistical analyses of water chemistry are presented in appendices E through H.
    - Principal potential pollutants—chapter 5 contains a discussion of potential pollution sources. Maps of these facilities are provided in figures 5-4 through 5-10.
- Estimate the quantity of water in the aquifers:
    - Data sufficient for a basin-wide, aquifer-specific assessment of groundwater quantity is not available. The complex geology of the Northeast River Basins does not lend itself to the general assumptions about aquifer properties, geometry, and saturated thickness that a plausible estimate of total and producible groundwater resources requires. The most important aquifers in the Northeast River Basins, including the Wasatch, Fort Union, and Madison formations, have been described in numerous, specific studies completed by the USGS (chap. 2) and WWDC (app. B) that are more comprehensive and relevant than a summary estimate. Groundwater resource estimates are addressed in this technical memorandum by analysis of recharge (chap. 6) and basin-wide water balances (chap. 8).
- Describe the aquifer recharge areas:
    - Plate 2 is a map of outcrop areas of aquifers and confining units in the Northeast River Basins. Maps depicting the outcrop areas used to calculate the annual rate of recharge for specific aquifers and groups of aquifers throughout the Northeast River Basins are provided in figures 6-1 through 6-6. Section 5.1 and chapter 6 discuss recharge.
- Estimate aquifer recharge rates:
    - Maps depicting average annual precipitation (fig. 3-3) and estimated recharge rates (fig. 5-2) over the NERB are presented in this technical memorandum. Existing annual recharge rates were multiplied by aquifer outcrop areas (figs. 6-1 through 6-6) to estimate a range of annual recharge volumes for individual and combined aquifers. The results of these estimates are summarized in tables 6-1 through 6-3 and discussed in section 6.2. Figure 6-7 represents recharge as a percentage of precipitation, and section 6.2 describes how recharge efficiency varies by individual and combined aquifers overall within the NERB.
- Discuss the concepts of "safe yield" and "sustainable yield," and describe implications of hydrologically connected groundwater and surface water:
    - The concept of "safe yield" is discussed in section 5.1.4. This report provides estimates of total recharge (average annual) for the NERB in chapter 6 and compares these recharge estimates to current groundwater withdrawals in chapter 8.
- Describe and evaluate existing groundwater studies and models:
    - Existing groundwater models are identified and evaluated, and recommendations for future groundwater modeling in the NERB are discussed in chapter 7.
- Identify future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands:
    - Several approaches to address future groundwater development potential are discussed throughout this report.
    - General and aquifer-specific hydrogeology relative to groundwater development potential is discussed in chapters 5 and 7.

  - Figures 8-1 through 8-7 show wells permitted by the SEO in the Northeast River Basins through October 7, 2015. These figures include selected groundwater permit statistics and illustrate historic groundwater development patterns relative to a sub-region's hydrogeologic unit outcrop patterns. Existing groundwater development in the NERB is discussed in chapters 7 and 8.
  - A summary of groundwater development studies and projects in the NERB, sponsored by the WWDC, is included in appendix B. The development potential of specific aquifers, based on information compiled from these and other studies, is described in chapter 7.
    - Groundwater development prospects identified in the groundwater resource investigations of the previous Powder/Tongue River Basin Water Plan (HKM Engineering and others, 2002a) and Northeast Wyoming River Basin Water Plan (HKM Engineering and others, 2002b) are discussed in chapter 9.
    - Current WWDC and SEO projects related to groundwater development in the NERB are discussed in chapter 9.

1.2 AGENCY PARTICIPATION

This technical memorandum is the result of a cooperative effort by the WWDC/WWDO, WSGS, USGS, and the Water Resources Data System (WRDS). The SEO and the Wyoming Department of Environmental Quality (WDEQ) contributed significant datasets for developing some of the figures presented in this technical memorandum.

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

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

The WSGS is a separate operating agency under the executive branch of state government (Wyoming State Statutes 9-2-801 and 9-2-803 through 9-2-810). The WSGS' purposes are: 1) to study, examine, and understand the geology, mineral resources, and physical features of the state; 2) to prepare, publish, and distribute (free or for a nominal price) reports and maps of the state's geology, mineral resources, and physical features; and 3) to provide information, advice, and services related to the geology, mineral resources, and physical features of the state. The survey's mission is to "promote the beneficial and environmentally sound use of Wyoming's vast geologic, mineral, and energy resources, while helping protect the public from geologic hazards." By providing accurate information and expanding knowledge through the application of geologic principles, the WSGS contributes to the economic growth of the state. WSGS hydrogeologists conduct research, compile data, create and distribute maps and reports, and address inquiries to assist citizens, industry, and state and federal agencies in planning, decision-making, and analysis of water issues.

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

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

The SEO and WWDO cooperate on many projects. SEO personnel attend meetings on river basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the SEO and WDEQ (K. Clarey, WWDO, personal commun., 2017).

1.3 LEGAL AND INSTITUTIONAL FRAMEWORK

Wyoming laws that govern the appropriation, development, and beneficial use of water resources are based on the doctrine of prior appropriation, commonly stated as "first in time is first in right" (Jacobs and others, 2003). This means that, during periods of limited supply, the first party to put a source of water to beneficial use has a "priority" water right honored prior to those of other, later users. An exception is that municipalities can obtain water rights from earlier priority uses through eminent domain (Wyoming State Statutes 1-26). The Wyoming Constitution establishes that all natural waters are property of the state. Therefore, a water right does not grant ownership, but only the right to use water for beneficial purposes. Use of water resources for domestic and livestock purposes customarily takes precedence over other uses. In Wyoming, water rights are attached to the land and can be transferred. The laws and regulations pertaining to the appropriation, development, and beneficial use of groundwater are administered by the SEO and Board of Control, a panel comprised of the superintendents of the four state water divisions and the state engineer. Most of the Northeast River Basins area is included in SEO Water Division II; the small Niobrara River Basin lies in Division I. The SEO website provides summary documents that examine pertinent aspects of Wyoming water resource law at: http://seo.wyo.gov/documents-data.

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 (Jacobs and others, 2003). The SEO is authorized for the permitting and orderly development of groundwater in Wyoming and has shared authority for protecting groundwater resources from waste and contamination. The updated Wind/Bighorn River Basin Water Plan (MWH and others, 2010) provides the following discussion of Wyoming water law specific to groundwater:

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

1.3.2 Interstate agreements

Wyoming is a "headwater" state. In most river basins, major portions of stream outflows into neighboring states originate in Wyoming (WWC Engineering and others, 2007). However, large volumes of these Wyoming sourced streamflows are allocated to priority water rights holders in downstream states. Streamflow allocations for most of Wyoming's rivers are defined by interstate compacts, international treaty, or court decree (SEO, 2006). The more recent agreements, notably in the Platte River and Bear River basins, recognize groundwater extraction can deplete streamflows, and include provisions limiting groundwater use in Wyoming.

The river basins examined in this report consist of the Wyoming portions of the Little Bighorn, Tongue, Powder, and Little Powder rivers of the Yellowstone River system, and the drainage basins of the Little Missouri, Belle Fourche, Cheyenne, and Niobrara rivers. Small areas in Montana, South Dakota, and Nebraska that are tributary to these Wyoming drainages are also included in some analyses presented in this report (fig. 3-1).

Three interstate stream compacts regulating the river basins in northeast Wyoming include:

- The Yellowstone River Compact of 1950, signed by Montana, Wyoming, and North Dakota, which regulates the Little Bighorn, Tongue, Powder, and the Little Powder Rivers in Wyoming, designates the division of waters and unallocated flows among the signatory states, and exempts future stock and domestic uses from provisions of the compact. The compact considers surface flows only and does not place any regulation on the allocation or development of groundwater.
- The Belle Fourche River Compact of 1943, signed by Wyoming and South Dakota, governs surface water rights and use in the Belle Fourche River Basin in Wyoming but does not contain restrictions on groundwater use in either state.
- The Upper Niobrara River Compact of 1962, signed by Wyoming and Nebraska, regulates Wyoming's use of the Niobrara River by defining storage and streamflow rights and priority dates. This compact also establishes the legal foundation for future groundwater apportionment in the Niobrara Basin.

All interstate compacts regulating streamflows in Wyoming are available for review at: http://seo.wyo.gov/interstate-streams. Appendix D contains copies of the Yellowstone, Belle Fourche, and Niobrara compacts.

1.3.3 Wyoming water law— groundwater quality

The Denver office of the U.S. Environmental Protection Agency (EPA) Region 8 has primary control (primacy) over Wyoming's public drinking water supplies. Wyoming is the only state in which EPA has primacy over drinking water systems. The EPA monitors water quality for several hundred public water systems in Wyoming. Information about Wyoming's public drinking water systems is available on the EPA Wyoming Drinking Water website at: https://sdwisr8.epa.gov/Region8DWWPUB/index.jsp.

Except on the Wind River Indian Reservation, the WDEQ enforces groundwater quality regulations under the Wyoming Environmental Quality Act, with guidance from the Wyoming Environmental Quality Council.

The WDEQ administers provisions of the federal Clean Water Act Amendment of 1972 (Section 208) that provide for water quality management by state and local governments, as well as provisions of the Federal Water Pollution Act, by developing a State Water Quality Plan approved by the EPA. In general, operations that cause groundwater contamination under the jurisdiction of the Wyoming Oil and Gas Conservation Commission (WOGCC), U.S. Bureau of Land Management (BLM), EPA, or U.S. Forest Service are referred to the WDEQ. The WOGCC has jurisdiction over Class II underground injection wells (chapter 5) dedicated to disposal of produced water from state and federal oil and gas leases.

1.3.4 Other agencies

The U.S. Bureau of Reclamation (BOR), an agency under the U.S. Department of the Interior, oversees and manages water resources specifically related to the operation of numerous water diversions, delivery, storage, and hydroelectric power generation projects built by the federal government throughout the western United States. The BOR cooperates with the SEO and the WWDC, but as a federal agency, has autonomy to execute some programs unilaterally. The BOR coordinates releases from Wyoming's reservoirs with the SEO (K. Clarey, WWDO, personal commun., 2017). Although not a primary area of concern, the BOR and the following other agencies are occasionally involved in groundwater resource issues:

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

1.4 AUTHORSHIP

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

Chapter 8: James E. Stafford, WSGS, Laramie, Wyoming

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The SEO provided groundwater permit data for Wyoming. We would like to express gratitude specifically to George Moser from the SEO for answering inquiries and assisting with quality control checks.

WDEQ contributed several data sets that are presented on the potential aquifer contaminant figures. Special thanks are expressed to Chad Kopplin, Matthew Kunze, James O'Connor, William DiRienzo, Jonathan Deutscher, Cindi Martinez, and Marcia Murdock at the WDEQ. Chris Nicholson and Tony Bergantino at WRDS helped obtain data and access reports from their library. Alec Osthoff provided technical review of the report. Jeff Hammerlink from the Wyoming Geographic Information Science Center (WyGisc) provided the data used to describe aquifer sensitivity and recharge.

WSGS Director Erin Campbell and former Director Tom Drean provided guidance and support throughout the project. WSGS Map Editor Suzanne Luhr supplied map editing and direction. We also recognize Christina George and James Rodgers for document preparation and layout. At the WSGS, Tomas Gracias and James Stafford developed the digital cartography for plates I and II and figures in chapters 1-6, 8 and 9; Suzanne Roberts, USGS illustrator, generated plates 3–6, 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.

Chapter 2

Background

Karl G. Taboga

The data contained in this basin groundwater update were obtained from regional and area-specific studies conducted by state and federal agencies in Nebraska, Montana, South Dakota, and Wyoming. This chapter discusses the data sources, approach, organization, and mapping through Geographic Information Systems (GIS) used in this study, and compares these points to the previous Groundwater Technical Memoranda contained within the 2002 Powder/Tongue (HKM Engineering and others, 2002a) and Northeast River Basin Water Plans (HKM Engineering and others, 2002b).

The 2002 Powder/Tongue (HKM Engineering and others, 2002a) and Northeast River Basin Water Plans (HKM Engineering and others, 2002b) and the 2007 Wyoming Framework Water Plan (WWC and others, 2007) are cited frequently in this study. In this report, online links are provided to these earlier studies and other sources of data.

2.1 SOURCES OF DATA

Agencies that contributed data and information for this study include:

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

2.2 PREVIOUS REGIONAL-SCALE INVESTIGATIONS

Numerous surface water and groundwater management studies have been conducted for areas contained wholly or partly within the combined Powder, Tongue, and Northeast river basins. The geographic scale of these earlier projects varies considerably. This study builds on these previous compilations. Primary hydrogeologic studies and associated supporting geologic investigations of the basin area are listed below in approximate chronologic order by agency and author(s). Notes have been included in italics to explain relevant content for some citations, as well as online links to agency websites where full content publications may be found.

- *U.S. Geological Survey Hydrologic Investigation Atlases (https://pubs.er.usgs.gov/)*

1973 - Hodson, W.G., Pearl, R.H., and Druse, S.A., 1973, Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Hydrologic Atlas 465, 4 pl., scale 1:250,000. Study area of HA-465 encompasses all river basins examined in this groundwater memorandum excepting the Niobrara River Basin.

1980 - Gutentag, E.D., and Weeks, J.B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Atlas 642, 1 pl., scale 1:2,500,000. Includes Niobrara and parts of Cheyenne River basins.

1981 - Weeks, J.B., and Gutentag, E.D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the high plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Atlas 648, 2 pl., scale 1:2,500,000. Includes Niobrara and parts of Cheyenne River basins.

1982 - Kroethe, N.C., Oliver, J.W. and Weeks, J.B., 1982, Dissolved solids and sodium in water from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Atlas 658, 2 pl., scale 1:2,500,000. Includes Niobrara and parts of Cheyenne River basins.

Luckey, R.R., Gutentag, E.D. and Weeks, J.B., 1982, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Atlas 652, 2 pl., scale 1:2,500,000. Includes Niobrara and parts of Cheyenne River basins.

1990 - Bedinger, M.S., and Langer, W.H., 1990, Reconnaissance study of the thickness of the unsaturated zone in the western conterminous United States: U.S. Geologic Survey Hydrologic Investigations Atlas HA-715, 1 pl., scale 1:2,500,000. Includes thickness data for Bighorn Mt. headwaters of Powder, Tongue and Little Bighorn rivers.

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

2002 - Bartos, T.T., Hallberg, L. L., and Ogle, K.M., 2002, Potentiometric surfaces, altitudes of the tops, and hydrogeology of the Minnelusa and Madison aquifers, Black Hills area, Wyoming: U.S. Geologic Survey Hydrologic Investigations Atlas HA-748, [variously paged].

Carter, J.M., Driscoll, D.G., Williamson, J.E., and Lindquist, V.A., 2002, Atlas of water resources in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA–747, 120 p.

- *Basin studies (http://library.wrds.uwyo.edu/) by the University of Wyoming, Water Resources Research Institute, and the Wyoming Natural Resource Board*

1961 - Dana, G.F., 1961, Underground water report for the city of Sundance, Wyoming: report prepared by Wyoming Natural Resources Board, Cheyenne, Wyoming, [variously paged].

1962 - Dana, G.F., 1962, Groundwater reconnaissance study of the State of Wyoming—Introduction and seven basin reports: Prepared for Wyoming Natural Resource Board, Cheyenne, Wyoming, 355 p.

1972 - Wyoming State Engineer's Office, 1972, Water & related land resources of northeastern Wyoming: Wyoming Water Planning Program, Cheyenne, Wyoming, Report No. 10, 180 p.

1977 - Davis, R.W., and Rechard, P.A., 1977, Effects of surface mining upon shallow aquifers in the eastern Powder River Basin, Wyoming: Laramie, University of Wyoming, Water Resources Research Institute Water Resources Series no. 67, 47 p.

Wyoming State Engineer's Office, 1977, Report on the Gillette project—A system of water wells in the Madison Formation and pipeline transmission to the Gillette area: Wyoming Water Planning Program, Cheyenne, Wyoming, 59 p.

1979 - Wells, D.K., 1979, Chemical analyses of water from the Minnelusa Formation and equivalents in the Powder River Basin and adjacent areas, northeastern Wyoming—A basic-data report: Wyoming Water Planning Program, Cheyenne, Wyoming, Report No. 18, 31 p.

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- *Wyoming Water Development Commission Project Reports are listed in Appendix B and are available online at: http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html. Project reports are listed in Appendix B, alphabetized by location, and include brief project descriptions and summary project recommendations. Separate associated publications (executive summaries, interim reports and appendices) are also available on the WRDS website, and are noted in italics following each citation.*

2.3 CURRENT WWDC AND USGS HYDROGEOLOGIC INVESTIGATIONS IN THE POWDER/TONGUE/NORTHEAST RIVER BASINS

Currently, the WWDO is updating the 2002 Powder/Tongue (HKM Engineering and others, 2002a) and Northeast River Basin Water Plans (HKM Engineering and others, 2002b). Additionally, WWDO is presently conducting groundwater studies in Buffalo, Clearmont, Lusk, and Newcastle. WWDO is also studying the feasibility of connecting the Buckskin, Fox Ridge, and Grace Land communities to the Gillette Regional Water Supply. The U.S. Geological Survey (USGS) is not currently conducting specific hydrogeologic investigations in the NERB. However, recent USGS reports which discuss the hydrogeology of the Powder River and Williston structural basins (Long and others, 2014; Thamke and others, 2014) in detail can be obtained from the USGS publications website: http://pubs.er.usgs.gov/. Additionally, the USGS continues to collect real time streamflow data and periodic water quality at twenty-one USGS gaging stations located in the NERB: http://waterdata.usgs.gov/wy/nwis/current/?type=flow.

2.4 CURRENT AVAILABLE GROUNDWATER DETERMINATION

The above noted previous investigations examined the hydrogeology of geographic areas of varying scale that fall partly or entirely within the NERB. The study area of this and the previous memoranda (HKM Engineering, 2002a, b) include the surface drainages of the NERB that lie within the borders of the state of Wyoming, as well as watersheds that are tributary to the Wyoming NERB in Montana, South Dakota, and Nebraska (fig. 3-1).

A detailed hydrostratigraphy of the NERB was developed by the USGS for this study based on stratigraphic regions by Love and others (1993). Development of the updated hydrostratigraphy is described in chapter 7 and summarized on hydrostratigraphic nomenclature charts (pls. 4-6), and on plate 2.

This Available Groundwater Determination provides expanded information on several topics to more fully characterize the groundwater resources of the NERB, including:

- Effects of structure on groundwater distribution and flow (section 5.4 and chapter 7)
- Potential hydrothermal resources (chapter 4)
- Aquifer vulnerability and potential sources of groundwater contamination (section 5.6)
- Comparisons of calculated aquifer(s)—specific recharge volumes with updated precipitation data, and current and projected beneficial uses (section 6.2)
- A basin-wide water balance (chapter 8)
- A detailed listing and summary of historic groundwater development studies by the WWDC in the NERB (Appendix B)

2.5 MAPS

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

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

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

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

Chapter 3

Description of the study area

Karl G. Taboga and James E. Stafford

This study examines groundwater resources that underlie the aggregated Powder/Tongue/Northeast River Basins (collectively designated in this report by the acronym "NERB") in Wyoming, as well as tributary areas in Montana, South Dakota, and Nebraska (fig. 3-1). The NERB in Wyoming covers approximately 23,223 mi^2 (14.86 million acres), or 23.75 percent of Wyoming's surface area. Tributary watersheds in the neighboring states are small, about 613 mi^2 (0.39 million acres). In Wyoming, the NERB includes all of Sheridan, Campbell, Crook, and Weston Counties, 98 percent of Johnson, 93 percent of Niobrara, 50 percent of Converse, 33 percent of Natrona, and 4 percent of Goshen counties. In Montana, the tributary watershed covers 3 percent of Bighorn, 1 percent of Powder River, and 4 percent of Carter Counties. In South Dakota, the NERB encompasses 6 percent of Custer County, and 5 percent of both Lawrence and Pennington Counties. The NERB covers 1 percent of Sioux County in Nebraska. Unless specific references are made to the tributary areas outside of Wyoming, references to the NERB in this memorandum refer only to the Wyoming portion.

The NERB encompasses about 23.75 percent of Wyoming's total surface area and serves as home to approximately 102,000 people, or about 17 percent of the state's population (Wyoming Department of Administration and Information Economic Analysis Division, 2016). The NERB contains 19 incorporated municipalities, 17 unincorporated communities, 11 U.S. Census Designated Places (CDP; table 3-1), and a substantial rural population. The map in figure 3-1 shows townships, major roads, and incorporated municipalities within the NERB.

3.1 GEOGRAPHIC EXTENT, PHYSIOGRAPHY, GEOMORPHOLOGY, AND SURFACE DRAINAGE

The NERB consists of eight contiguous river drainages located in the northeastern quarter of Wyoming and small tributary areas in neighboring states (table 3-2). Streamflows from all eight rivers move from Wyoming into neighboring states, and ultimately discharge to the Missouri River. Data from several decades of USGS stream gauge stations tracking average annual streamflows out of Wyoming are also shown in table 3-2 (Stafford and Gracias, 2009).

Table 3-1. Communities located in the NERB.

Municipalities	Unincorporated communities	Census designated places
Buffalo	Aladdin	Antelope Valley
Clearmont	Alva	Arvada
Dayton	Arminto	Beulah
Edgerton	Banner	Big Horn
Gillette	Beulah	Hill View Heights
Hulett	Bill	Lance Creek
Kaycee	Four Corners	Osage
Lusk	Hiland	Parkman
Manville	Leiter	Powder River
Midwest	Linch	Sleepy Hollow
Moorcroft	Natrona	Story
Newcastle	Recluse	----
Pine Haven	Rozet	----
Ranchester	Saddlestring	----
Sheridan	Weston	----
Sundance	Wolf	----
Upton	Wyarno	----
Van Tassell	----	----
Wright	----	----

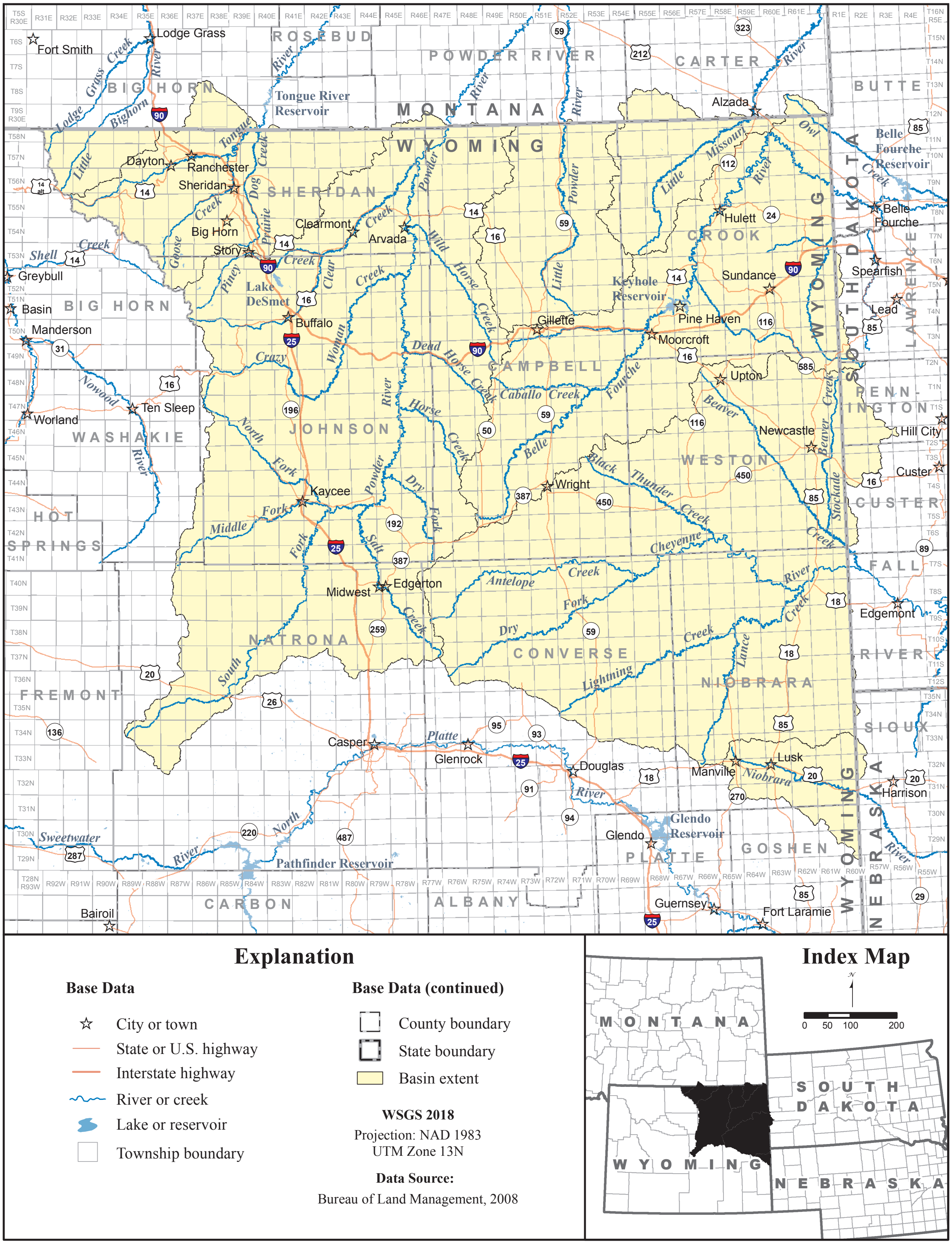


Figure 3-1. Municipality, road, township, and range index map, NERB, Wyoming.

Table 3-2. Physical characteristics of the river drainages that compose the NERB.

River Drainage[1]	Total surface area (mi^2) covered by this report[1]	Drainage surface area (mi^2) located in Wyoming[1]	Neighboring states with tributary areas[1]	Average annual streamflows (CFS) out of Wyoming [2]
Little Bighorn River	302	299	Montana	173
Tongue River	1,737	1,609	Montana	430
Powder River	7,979	7,951	Montana	438
Little Powder River	1,381	1,378	Montana	20
Little Missouri River	828	725	Montana	80
Belle Fourche River	3,968	3,881	Montana, South Dakota	116
Cheyenne River	7,043	6,813	South Dakota	85
Upper Niobrara River	550	532	Nebraska	4

[1] NRCS, 2016	*NRCS, 2016, Watershed Boundary Dataset overview, history of hydrologic units and supporting documents: http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/ngce/.
[2] Stafford and Gracias, 2009	Stafford, J.E., and Gracias, T., 2009, Surface water resource map of Wyoming—Streamflows and storage: Wyoming State Geological Survey Map Series 91, scale 1:500,000.

The NERB is located within the Great Plains, Middle Rocky Mountain, and Wyoming Basin Physiographic Provinces. Major physiographic features, drainages, and reservoirs of the NERB are shown on figure 3-2 and plate 1. A map of the physiographic provinces of Wyoming is available online at: http://www.wsgs.wyo.gov/products/wsgs-1989-es-1.pdf (Roberts, 1989).

The geomorphology of the NERB (fig. 3-2) is dominated by heavily eroded Laramide-aged uplifts that border deep intermountain structural basins, which are filled with sediments eroded from the uplifts. The Laramide uplifts are composed of large anticlines that have crystalline basement cores. Erosion of the uplifts has exposed older geologic formations at higher elevations. Precambrian basement rocks crop out along the ridges of the Bighorn Mountains and Hartville uplift. Paleozoic sedimentary units are exposed in the Black Hills and Rattlesnake Hills. Mesozoic formations are exposed in the Casper Arch. The Black Hills and Rattlesnake Hills contain igneous rocks formed during brief periods of early Tertiary volcanic activity that likely occurred in the waning stages of the Laramide orogeny.

The largest geologic structure is the Powder River Structural Basin (PRSB), an elongate Laramide foreland basin measuring 200 miles north to south by nearly 120 miles east to west. The structural basin is asymmetric—it dips gently westward (~1.5°) from its eastern margin for about 90 miles to the basin's axis, where it reaches its greatest depths (~18,000 ft below the surface). The basin axis is within 10 miles of its western edge and generally parallels the ridge of the Bighorn Mountains. Earliest formation of the PRSB likely occurred in the middle Paleocene when rapid subsidence (Curry, 1971) created Lake Lebo, which was subsequently in-filled by fluvial, deltaic, paludal (marshy), and lacustrine deposition of eroded sediments from nearby uplifts. The Paleocene Fort Union Formation crops out along the basin margins and is overlain by the Eocene Wasatch Formation (plate 1).

A small portion of the NERB extends onto the northeast margin of the Wind River Structural Basin (plate 1, fig. 3-2) where the South Fork of the Powder River drains the northern flank of the Rattlesnake Hills. Additionally, the Upper Niobrara River drainage of the NERB extends into the northern Denver-Julesburg Structural Basin.

Detailed discussion of the geology of the NERB is provided in chapters 4 and 7 of this study.

The area of the NERB is bound by the Bighorn Mountains on the west, the Casper Arch and Rattlesnake Hills to the southwest, the Hartville Uplift to the southeast, and the Black Hills in the northeast. The NERB is open to the north where the PRSB continues into Montana, and also along the eastern border of Wyoming between the Black Hills and the Hartville uplift. The Little Bighorn, Tongue, Powder, Little Powder, and Little Missouri Rivers flow out of Wyoming from the northern PRSB into Montana. The Cheyenne and Upper Niobrara Rivers enter South Dakota and Nebraska, respectively, across Wyoming's eastern border between the Black Hills and the Hartville uplift. The Belle Fourche River flows

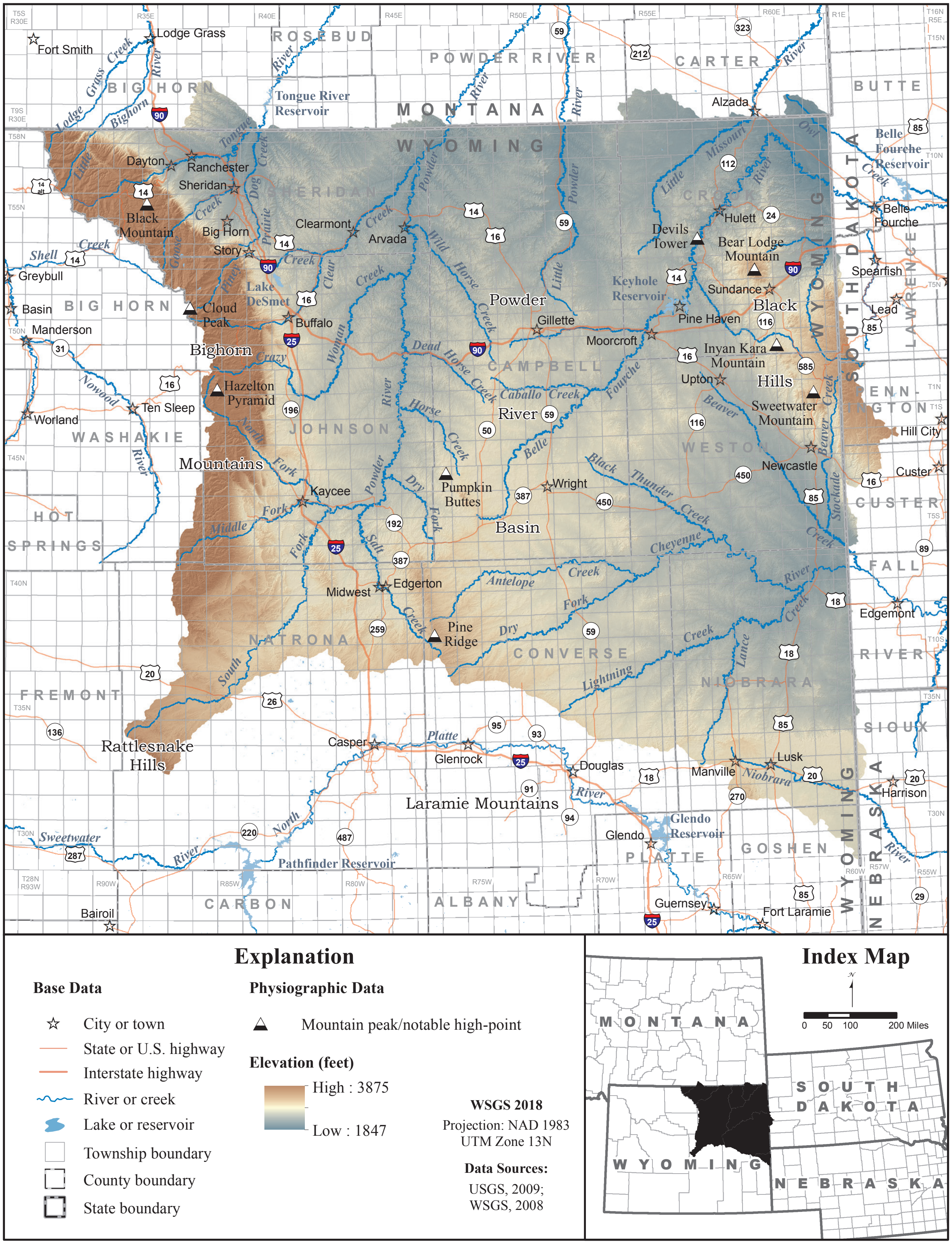


Figure 3-2. Physiographic features, drainages, and bodies of water, NERB,Wyoming.

northeast around the northern end of the Black Hills, then makes an abrupt turn to flow southeastward into South Dakota.

Perennial streams in the NERB receive a large percentage of their source waters from overland flow associated with snowmelt and rainfall that originates in semi-humid mountains and highlands, headwater regions, and from persistent baseflow. Most ephemeral flow occurs in response to springtime snowmelt and to intense, short duration, rainfall events characteristic of transient, convective thunderstorms. Streamflows are also affected by vegetation, temperature, artificial diversions, and complex interconnections with groundwater.

3.2 CLIMATE, PRECIPITATION, AND VEGETATION

Climate within the NERB is primarily a function of elevation, though latitude and topography play lesser roles. Climate types range from semi-arid continental within the interior basins to humid-alpine in the bordering mountain ranges. The Bighorn Mountains capture much of the atmospheric moisture through orographic uplift, resulting in increased annual precipitation while substantially decreasing precipitation in the basin interiors. Temperature varies by season from well below 0°F in the winter to more than 100°F in the summer. Annual precipitation increases with surface elevation (fig. 3-3) and can exceed 41 inches a year in the high mountain headwater areas of the Powder River and Tongue River drainages. Annual precipitation averages 15 inches over the entire basin (PRISM, 2016). Most precipitation within the basin occurs as snowfall during the winter and early spring, and as convective thunderstorms during late spring and summer months (Feathers and others, 1981).

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

3.3 POPULATION DISTRIBUTION, LAND USE, AND LAND OWNERSHIP

The Wyoming Department of Administration and Information Economic Analysis Division (WDAIEAD) estimates 102,000 people, or about 17 percent of the state's population (WDAIEAD, 2016), reside in the Wyoming portion of the NERB. The basin contains 19 municipalities and 11 U.S. Census Designated Places (U.S. Census Bureau, 2010) in Wyoming; most of these communities are located along or within a few miles of rivers or creeks (fig. 3-1).

Land use in the NERB is controlled primarily by elevation, climate, precipitation, and land ownership. Above timberline, the alpine areas are generally used for recreational purposes. At lower elevations, densely forested areas are utilized for recreation and limited logging. Grazing is the dominant use for rangelands, foothills, and riparian areas. Agriculture plays a significant role in the basin; approximately 1.7 percent (256,523 acres) of the basin's surface area consists of irrigated cropland (HKM and others, 2002a, b). Crop-producing areas in the Powder River Basin are located mainly along the Upper Tongue River, Clear Creek, Crazy Woman Creek, Powder River, and Little Powder River (HKM and others, 2002a, b). Other drainages in the NERB with significant irrigated acreages include the Little Missouri, Belle Fourche, Cheyenne, and Niobrara Rivers (HKM and others, 2002a, b). A map illustrating the distribution of the broad categories of land cover in the northwestern United States, with downloadable GIS land cover data, is provided online by the USGS at:https://gis1.usgs.gov/csas/gap/viewer/land_cover/Map.aspx .

Privately owned lands constitute about 70.4 percent of the land in the NERB, approximately 21 percent is federally owned, and 8.3 percent is owned by the State of Wyoming. Federal land in the basin is managed by the Bureau of Land Management (~1.68 million acres), the U.S. Forest Service (~1.45 million acres), and the National Park Service (1,361 acres). A map of state, federal, and private land ownership in Wyoming can be found online in Chapter 3 of the Wyoming Water Development Office's 2007 Statewide Water Plan (WWC Engineering and others, 2007) at http://waterplan.state.wy.us/frameworkplan-index.html.

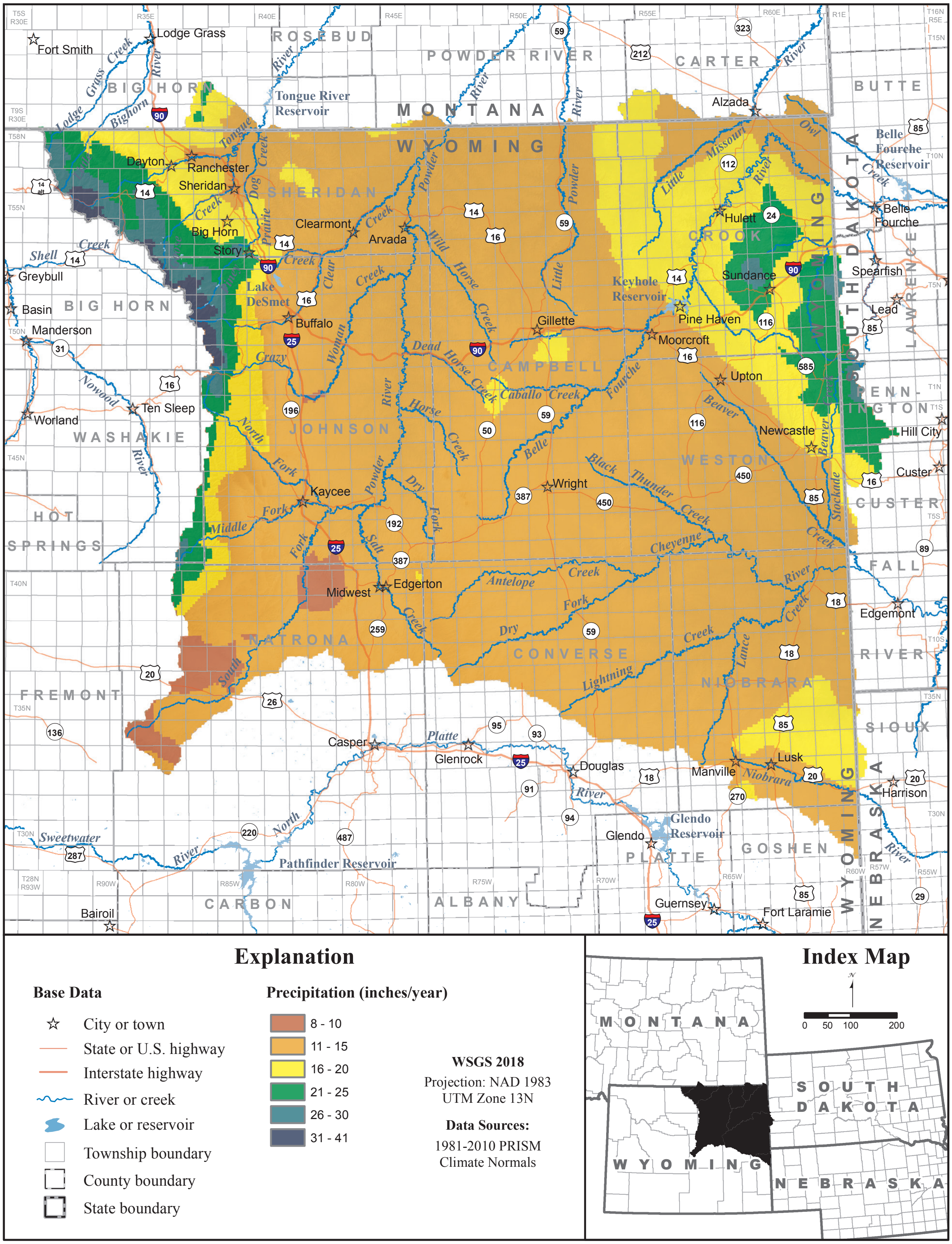


Figure 3-3. Average annual precipitation (1981–2010), NERB, Wyoming.

Chapter 4

Geologic overview

Andrea M. Loveland

The Northeast River Basins (NERB) study area covers approximately 14.86 million acres in northeastern Wyoming, southeastern Montana, western South Dakota, and western Nebraska. The geologic setting of the NERB includes Precambrian-cored uplifts formed during the Laramide orogeny and adjacent basins filled with Phanerozoic clastic and carbonate rocks. The following information regarding the NERB study area is provided in this chapter:

- An overview of the geologic history
- A summary of the structural geology
- An outline of significant mineral and energy resources
- Geologic cross sections

4.1 GENERAL GEOLOGIC HISTORY

During the Paleozoic Era, the area that is now the NERB was located on the western margin of the North American craton in a shelfal environment. Although there is some evidence of minor movement along zones of weakness within the cratonic basement (Slack, 1981; Maughan and Perry, 1986; Dolton and others, 1990), the region was tectonically stable and only underwent minor deformation in the form of gentle upwarping and subtle depressions.

Sediments deposited during the Paleozoic Era indicate episodic sea level shifts along the edge of the craton. Consequently, Paleozoic rocks in the NERB range from terrestrial and near-shore marine sandstones to marine shales and carbonates. Episodic late Paleozoic uplift events associated with the formation of the Ancestral Rocky Mountains to the south further influenced deposition of sediments across Wyoming (Maughan, 1993).

In the early Mesozoic Era, sea level fluctuations continued to be a major control on sediment deposition. During most of the Triassic Period, the NERB was a coastal plain environment where deposition of red beds occurred and are now observed, particularly in the Chugwater Group (Spearfish Formation Equivalent; Cavaroc and Flores, 1991).

As the Sevier orogeny began uplifting sedimentary cover rocks to form the mountain ranges of present-day western Wyoming (Royse, 1993), the NERB area was submerged in the Cretaceous Interior Seaway. A thick succession of shales with interbedded sandstone, siltstone, and limestone were deposited, indicating numerous sea level fluctuations until the final retreat of the seaway in the Late Cretaceous.

The Laramide orogeny commenced in the Late Cretaceous and continued through the Early Eocene. Crustal shortening was accommodated by displacement of Precambrian crystalline basement rocks and the overlying sedimentary cover rocks (Brown, 1993). Basement-cored Laramide structures border the NERB on three sides: 1) the Bighorn Mountains to the west, 2) the Black Hills to the east, and 3) the Rattlesnake Hills and Hartville Uplift to the south (fig. 4-1).

The geologic setting of the NERB study area is illustrated on the bedrock geologic map in plate 1. This map also displays surface water, highways, political boundaries, and state and county data. Inset maps on plate 1 show the distribution of lineaments and a structure-contour map of the top of the Precambrian basement. Nine cross sections show subsurface structure in the NERB (figs. 4-2 through 4-11). Descriptions of the Precambrian- through Tertiary-aged stratigraphic units exposed in the study area are included in appendix A, and are not addressed specifically in this chapter.

4.2 STRUCTURAL GEOLOGY

The NERB study area includes the Powder River Basin, the easternmost edge of the Wind River Basin, and the northernmost tip of the Denver-Julesburg Basin. Significant uplift structures that bound these basins are also a part of the study area. These include the Bighorn Mountains, Black Hills Uplift, Rattlesnake Hills, Casper Arch, and the Hartville Uplift (fig. 4-1). These and other significant structural features are discussed below.

4.2.1 Powder River Basin (PRB)

The Powder River Basin is an elongate, north-northwest-trending sedimentary and structural basin in northeastern Wyoming and southeastern Montana. The basin is bounded by Laramide Precambrian-cored uplifts on three sides: 1) the Bighorn Mountains to the west, 2) the Black Hills Uplift to the east, and 3) the Casper Arch and Hartville Uplift to the south (fig. 4-1). Reverse and thrust faults are present along the flanks of some of these uplifts, occasionally with a strike-slip offset component (Clarey, 2009). The geometry of the basin is asymmetric, with a steeply dipping to overturned western limb and a gently dipping eastern limb. The synclinal axis is positioned adjacent to the Bighorn Mountains near the western margin of the basin (Ver Ploeg and others, 2008). The maximum thickness of Phanerozoic rocks in the basin is 18,000 ft (Beikman, 1962).

4.2.2 Wind River Basin (WRB)

The Wind River Basin is a structural and sedimentary basin in central Wyoming. A portion of the eastern end of the northwest–southeast-trending basin is included in the NERB study area. Within the NERB, the WRB is bounded to the southwest by the Rattlesnake Hills and to the northeast by the Casper Arch and Bighorn Mountains (fig. 4-1). The basin formed during Laramide deformation as the trough subsided and mountains adjacent to the basin were uplifted. As the uplift structures began to erode, sediments were shed into the basin, resulting in the deposition of an 18,000-ft-thick sequence of Phanerozoic sediments, including fluvial and lacustrine sediments (Keefer, 1970).

4.2.3 Denver-Julesburg Basin (DJB)

The northernmost edge of the Denver-Julesburg Basin is included in the southeastern corner of the NERB study area (fig. 4-1). The DJB is a north-south-trending asymmetrical Laramide-aged basin that covers more than 70,000 mi^2 (180,000 km^2) in parts of Colorado, Wyoming, Kansas, and Nebraska. In the NERB, the DJB is bounded to the north by the Hartville Uplift. Most of the subterranean strata preserved in the DJB was deposited during the Laramide orogeny and is Cretaceous aged (Drake and others, 2014), however, most surface exposures in the basin are Tertiary, which in the NERB consists of the Arikaree Formation.

4.2.4 Bighorn Mountains

The Bighorn Mountains formed during the Laramide orogeny in the Rocky Mountain foreland (fig. 4-1). They are cored by Precambrian plutonic and metamorphic rocks that extend in an arcuate fashion from southcentral Montana to the northern margin of the Wind River Basin in central Wyoming. The Bighorn Mountains were thrust to the east and are flanked in the NERB study area by steeply dipping to overturned Paleozoic and Mesozoic sedimentary rocks on the east.

4.2.5 Hartville Uplift

The Hartville Uplift is a north–northeast-trending Laramide structural uplift along the southern margin of the NERB (fig. 4-1). It is superimposed upon and predates the Hartville Arch, which is a northeast-southwest-trending structure between the Powder River and Denver-Julesburg basins. Iron and copper are among the minerals mined in the Hartville mining district.

4.2.6 Black Hills

The Black Hills of Wyoming are the northwestern continuation of the Black Hills in South Dakota (fig. 4-1). It formed in the late stages of the Laramide orogeny by the intrusion of an alkaline igneous complex. The exposed basement consists of Precambrian igneous and metamorphic rocks, and is overlain by Paleozoic and Mesozoic clastic and carbonate rocks.

4.2.7 Casper Arch

The Casper Arch is bounded to the southwest by a west-southwest vergent, large-displacement foreland thrust fault that in the subsurface offsets Precambrian rocks above younger sedimentary rocks in the adjacent Wind River Basin (Skeen and Ray, 1983; fig. 4-1). Although it is an uplifted area, it is not uplifted significantly enough to form a mountain range with an exposed core of Precambrian rock. Upper Cretaceous marine shales are exposed at the center of the arch, with rocks as young as Paleocene exposed on its flanks.

4.2.8 Rattlesnake Hills

The Rattlesnake Hills are a Laramide uplift structure located along the southern margin of the Wind River Basin (fig. 4-1). They are a northwest-trending anticlinal structure in which the crystalline-cored fold is overlain by Phanerozoic rocks. Alkaline intrusive rocks are also exposed in the southern Rattlesnake Hills, and were emplaced after Laramide folding (Hoch and Frost, 1993). These exposures are not a part of the NERB study area, but are similar in age and structural setting, and share mineralogical and geochemical signatures with the alkaline igneous complex exposed in the Black Hills region of the NERB (Hoch and Frost, 1993).

4.2.9 Pine Ridge

Pine Ridge is a northwest–southeast-trending topographic high on the eastern margin of the Casper Arch (fig. 4-1). It serves as a hydrologic divide between the Powder River and Cheyenne River hydrologic basins. This area is part of the Powder River Basin uranium district.

4.2.10 Pumpkin Buttes

Pumpkin Buttes are a group of large, orange-colored Wasatch sandstone mesas in the central Powder River Basin that are overlain unconformably by a 30- to 50-ft-thick cap of White River Formation (Sharp and others, 1964; fig. 4-1). A significant uranium deposit was discovered here in 1951.

4.2.11 Red Hills

The Red Hills are clinker deposits that formed due to naturally burning coal beds (fig. 4-1). They have burned since at least the early Pliocene (Heffern and others, 2007). About 1,600 mi^2 (4,100 km^2) of the Powder River Basin is dominated by clinker-controlled topography, which forms resistant reddish layers that cap hills and buttes. In the Red Hills, exposures of the Tongue River Member of the Fort Union Formation are capped by resistant layers of clinker (Heffern and others, 2007).

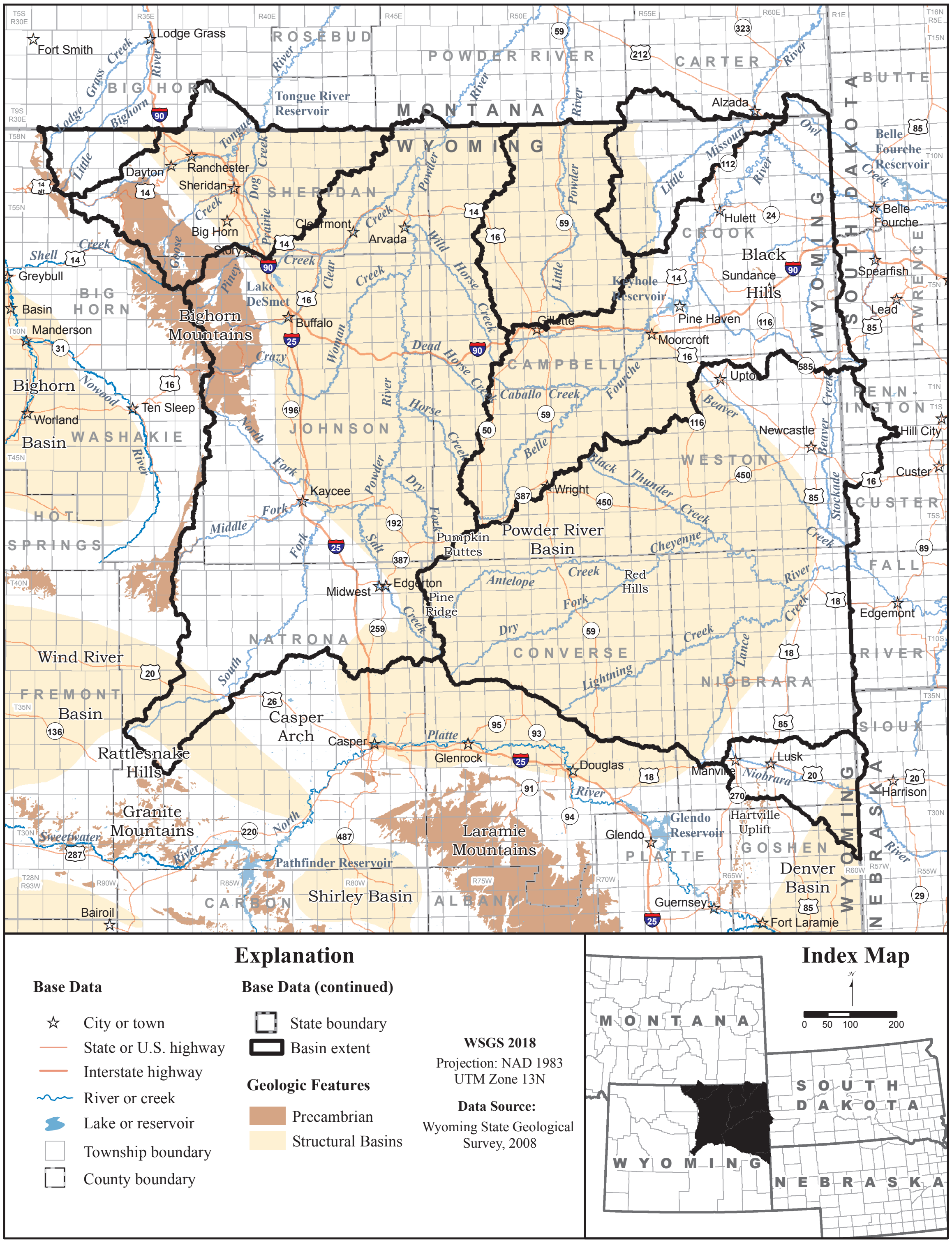


Figure 4-1. Geologic features in the NERB, Wyoming.

4.3 MINERAL AND ENERGY RESOURCES

The NERB is rich with various mineral and energy resources, including aggregate (clinker, limestone, and gravel), oil and gas (including coalbed methane), coal, gypsum, bentonite, and uranium (Harris and others, 1992). Iron and copper are mined in the Hartville mining district. Chapter 5 of this study identifies potential contamination sources related to the development of mineral and energy resources.

The most significant resources in the NERB are the near-surface coals mined in the Powder River Basin, which account for nearly half of all coal produced in the United States. Oil and gas, including coalbed natural gas, and uranium are also key resources in the NERB.

The following is a partial list of references that provide detailed information about the major mineral and energy resources in the NERB:

Powder River Basin

- Summary of mineral and energy resources in the Powder River Basin (Harris and others, 1992)
- Petroleum system assessment for the Powder River Basin (USGS, 2004; Anna, 2010)
- Uranium deposits in the Pumpkin Buttes area (Sharp and others, 1964)
- Coal geology and assessment of coal resources and reserves in the Powder River Basin (Luppens and others, 2015)

Wind River Basin

- Petroleum system assessment for the Wind River Basin (USGS, 2007)
- Mineral resources (Hausel and Holden, 1978)

Denver-Julesburg Basin

- Oil and gas in Denver-Julesburg Basin (USGS, 2007)

Black Hills

- Mineral resource potential (DeWitt and others, 1986)

4.4 GEOLOGIC CROSS SECTIONS

Plate 1 and fig. 4-2 show the locations of the geologic cross sections (figs. 4-3 through 4-11) provided in foldout figures at the end of this chapter. The cross sections, adapted from USGS and WSGS studies, also illustrate the progression of stratigraphic nomenclature in northeastern Wyoming from the early 1900s until now. The WSGS digitized the original cross sections and added colors to the geologic units generally consistent with the Geologic Map of Wyoming (Love and Christiansen, 1985). Geographic extents within the NERB for individual cross sections are noted below:

Sections A-A', B-B', and C-C' (figs. 4-3 through 4-5) are from Lynds (2013). Section A-A' extends through the Tongue River and Powder River drainages. Section B-B' passes from the eastern Powder River drainage through the Little Powder River and Belle Fourche drainages. Section C-C' goes through the central part of the Powder River drainage.

Sections D-D', E-E', and F-F' (figs. 4-6 through 4-8) are by Darton (1906). Section D-D' goes from the crest of the Bighorn Mountains through the Little Bighorn River drainage into the Tongue River drainage. Sections E-E' and F-F' extend from the crest of the Bighorn Mountains into the Powder River drainage. Stratigraphy in theses sections does not match Love and others (1993). The Parkman, Piney, DeSmet and Kinsbury (sic) combined unit (Kpd) occupy an interval currently comprised of the Wasatch, Fort Union and Lance formations, and Foxhills Sandstone (Love and others, 1993). The "Colorado Shales" unit (Kc) refers to a stratigraphic interval that stretches from the Fall River Formation through the Niobrara Formation of Love and others (1993). The "Embar" Formation is an abandoned unit name, widely used in past oil exploration, that has been replaced by the Park City, Dinwoody, and parts of the Chugwater formations, and their stratigraphic equivalents (USGS Geolex, 2018).

Section G-G' (fig. 4-9), obtained from Keefer (1970), passes through a small part of the Wind River Structural Basin located in the Powder River drainage.

Section H-H' (fig. 4-10), from DeWitt and others (1989), extends from the crest of the Black Hills through the Belle Fourche drainage into the Little Missouri River drainage.

Section I-I' (fig. 4-11), from McLaughlin and others (2011), passes through southern parts of the Niobrara River drainage.

The maps and studies that contain the original cross sections are available on the USGS National Geologic Map Database (https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl) and the USGS Publications Warehouse website (https://pubs.er.usgs.gov/).

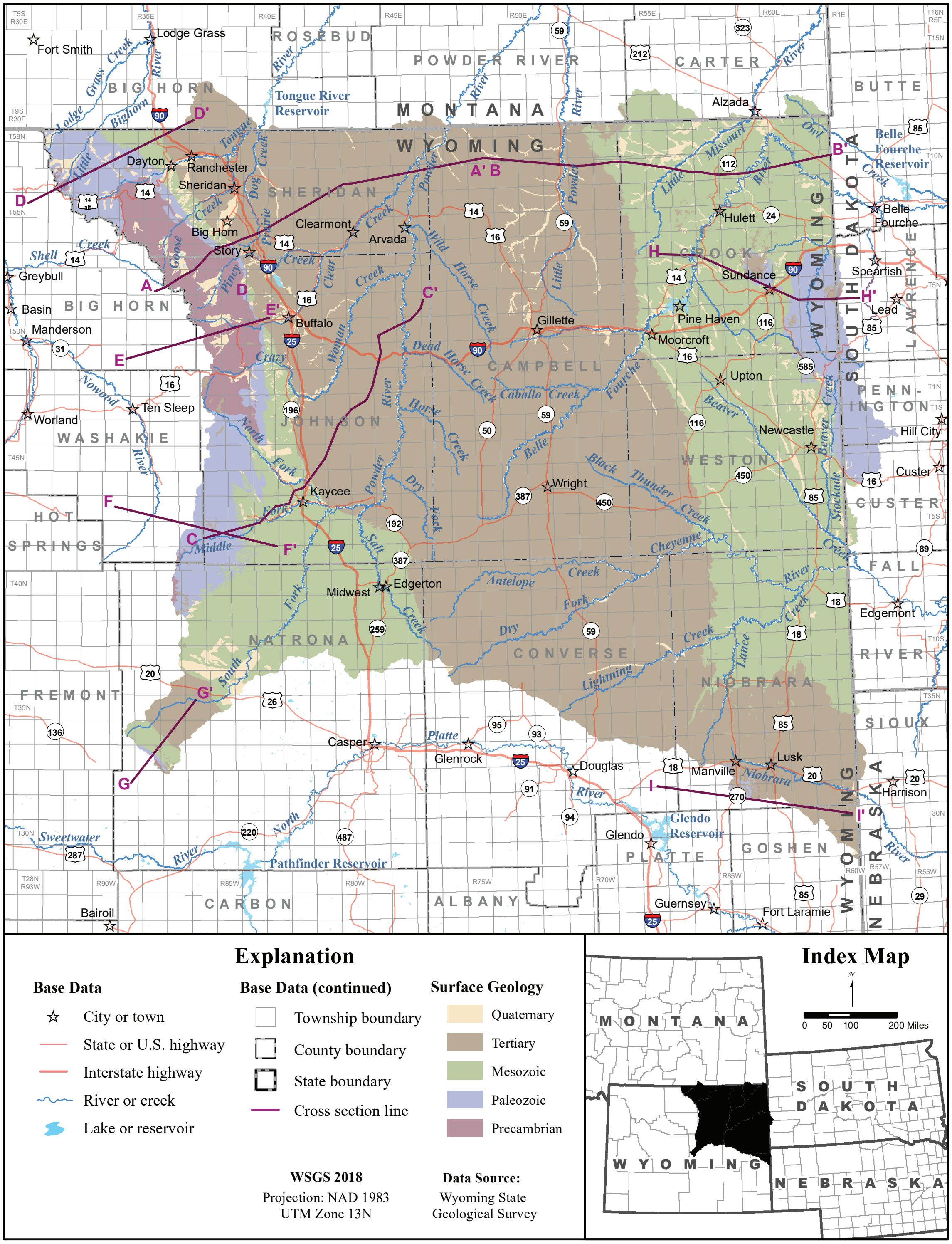
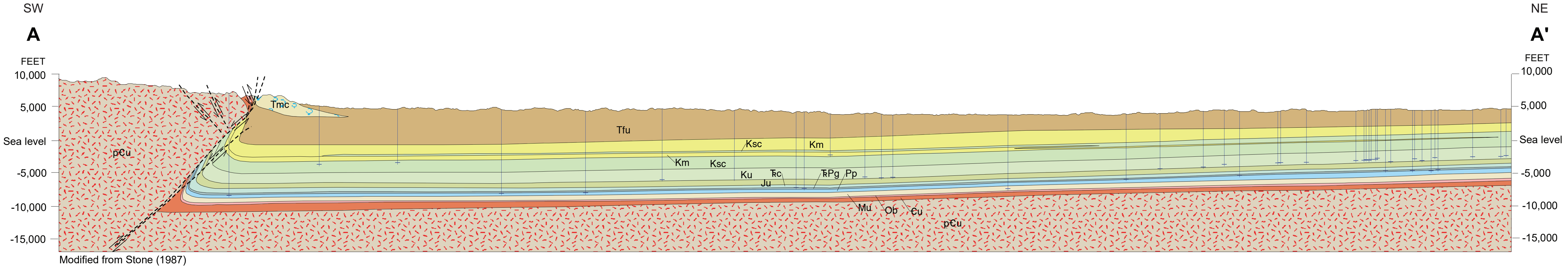


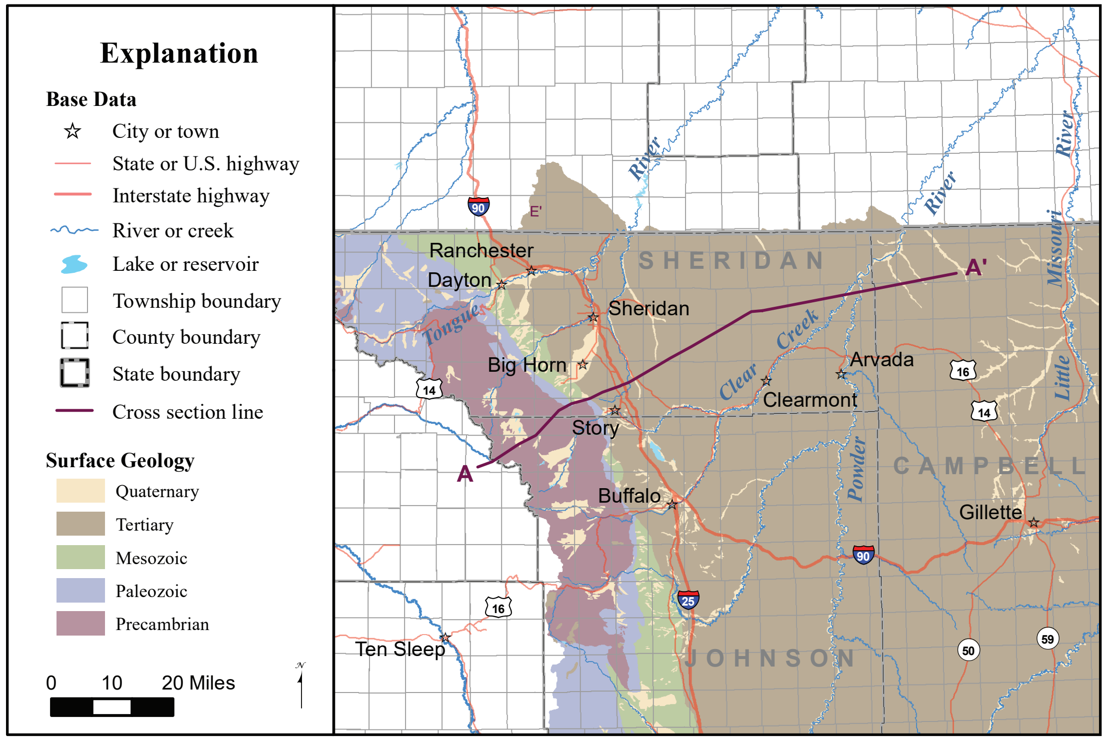
Figure 4-2. Locations of cross sections A-A' through I-I'.

Cross Section A-A’



Modified from Stone (1987)

Index Map and Line of Cross Section



Explanation

Symbols

- Formation contact – Dashed where inferred
- Fault – Dashed where inferred; arrows indicate relative movement
- Drill hole – Well logs used to construct cross section

Geologic Units

CENOZOIC
Tertiary

Symbol	Unit
Tmc	Moncrief and Kingsbury Conglomerate Members of Wasatch Formation
Tfu	Fort Union Formation

MESOZOIC
Cretaceous

Symbol	Unit
Km	Meeteetse Formation
Ksc	Skull Creek Shale
Ku	Cretaceous rocks, undifferentiated

Jurassic

Symbol	Unit
Ju	Jurassic rocks, undifferentiated

Triassic

Symbol	Unit
Ŧc	Chugwater Formation

PALEOZOIC
Permian

Symbol	Unit
Pp	Phosphoria Formation

Triassic and Permian

Symbol	Unit
ŦPg	Goose Egg Formation

Mississippian

Symbol	Unit
Mu	Mississippian rocks, undifferentiated

Ordovician

Symbol	Unit
Ob	Bighorn Dolomite

Cambrian

Symbol	Unit
Єu	Cambrian rocks, undifferentiated

PRECAMBRIAN

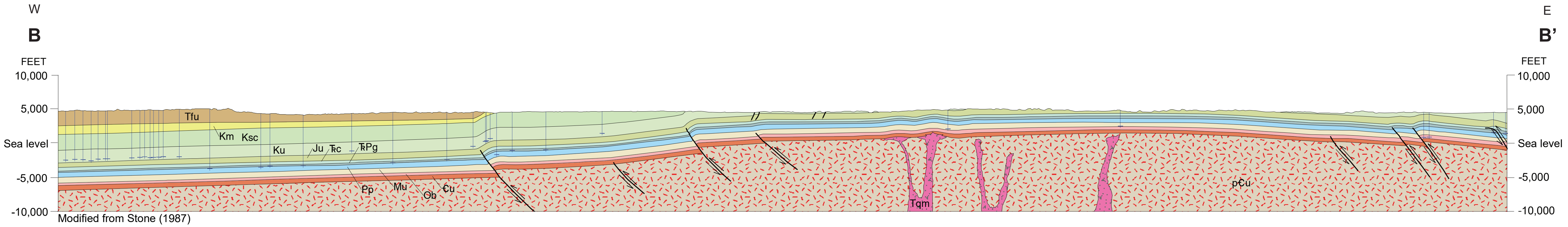
Symbol	Unit
pЄu	Precambrian rocks, undifferentiated

Adapted from:

Lynds, R.M., 2013, Geologic storage assessment of carbon dioxide (CO_2) in the Laramide basins of Wyoming: Wyoming State Geological Survey Technical Memorandum 3, 200 p., 20 pls.

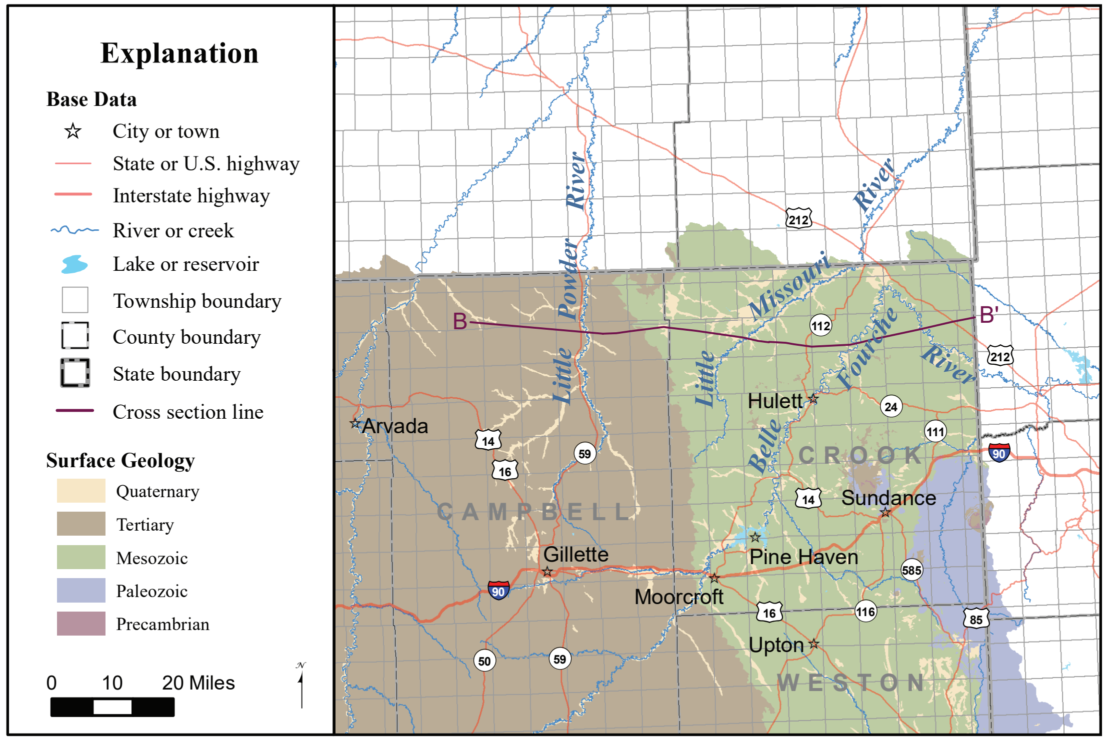
Figure 4-3. Geologic cross section A-A’.

Cross Section B-B’



Modified from Stone (1987)

Index Map and Line of Cross Section



Explanation

Symbols

Formation contact – Dashed where inferred

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross section

Geologic Units

CENOZOIC
Tertiary

Tqm	Quartz monzanite intrusion
Tfu	Fort Union Formation

MESOZOIC
Cretaceous

Km	Meeteetse Formation
Ksc	Skull Creek Shale
Ku	Cretaceous rocks, undifferentiated

Jurassic

Ju	Jurassic rocks, undifferentiated

Triassic

Ꞧc	Chugwater Formation

PALEOZOIC
Permian

Pp	Phosphoria Formation

Triassic and Permian

ꞦPg	Goose Egg Formation

Mississippian

Mu	Mississippian rocks, undifferentiated

Ordovician

Ob	Bighorn Dolomite

Cambrian

Ꞓu	Cambrian rocks, undifferentiated

PRECAMBRIAN

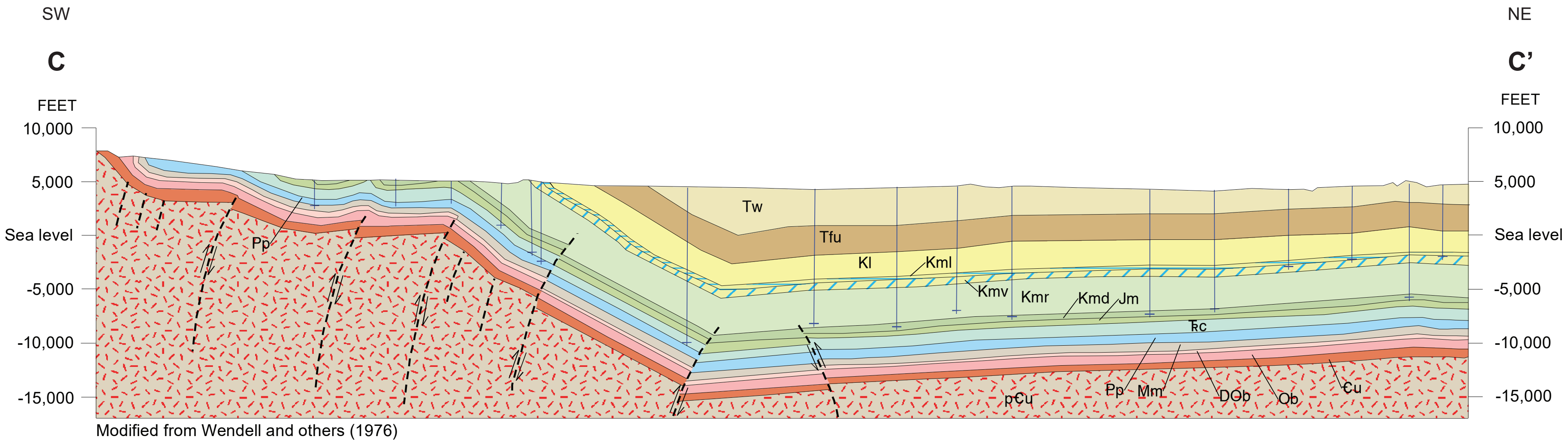
pꞒu	Precambrian rocks, undifferentiated

Adapted from:

Lynds, R.M., 2013, Geologic storage assessment of carbon dioxide (CO_2) in the Laramide basins of Wyoming: Wyoming State Geological Survey Technical Memorandum 3, 200 p., 20 pls.

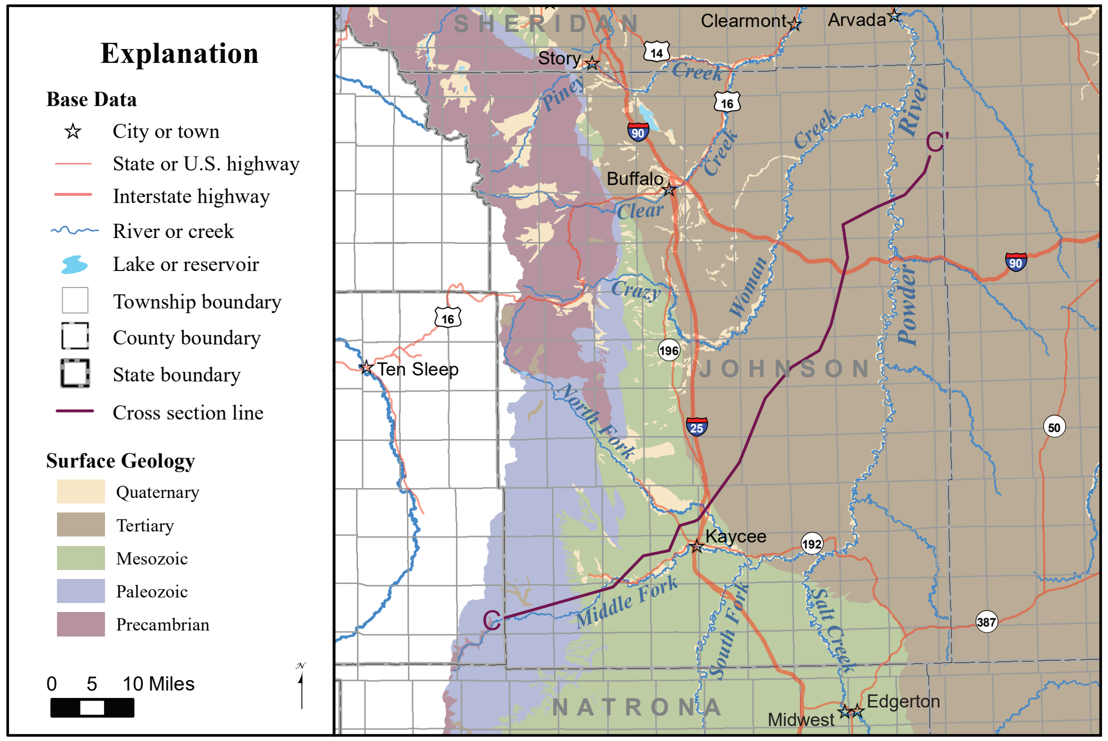
Figure 4-4. Geologic cross section B-B’.

Cross Section C-C’



Modified from Wendell and others (1976)

Index Map and Line of Cross Section



Explanation

Symbols

Formation contact – Dashed where inferred

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross section

Geologic Units

CENOZOIC
Tertiary

Tw Wasatch Formation

Tfu Fort Union Formation

MESOZOIC
Cretaceous

Kl Lance Formation

Kml Lewis Shale

Kmv Mesaverde Formation

Kmd Muddy Sandstone

Kmr Mowry Shale

Jurassic

Jm Morrison Formation

Triassic

Ʀc Chugwater Formation

PALEOZOIC
Permian

Pp Phosphoria Formation

Mississippian

Mm Madison Limestone

Devonian and Ordovician

DOb Devonian rocks and Bighorn Dolomite, undifferentiated

Ordovician

Ob Bighorn Dolomite

Cambrian

Ꞓu Cambrian rocks, undifferentiated

PRECAMBRIAN

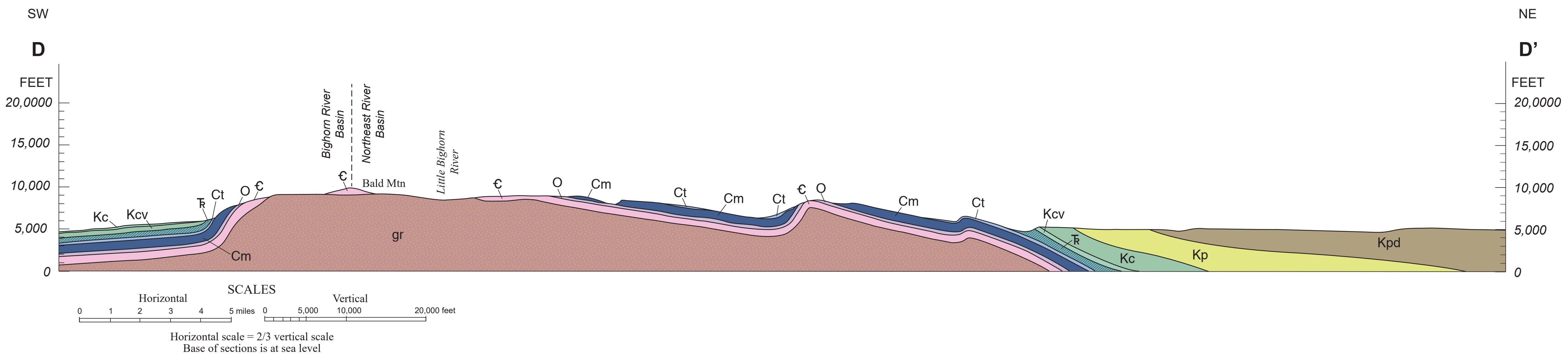
pCu Precambrian rocks, undifferentiated

Adapted from:

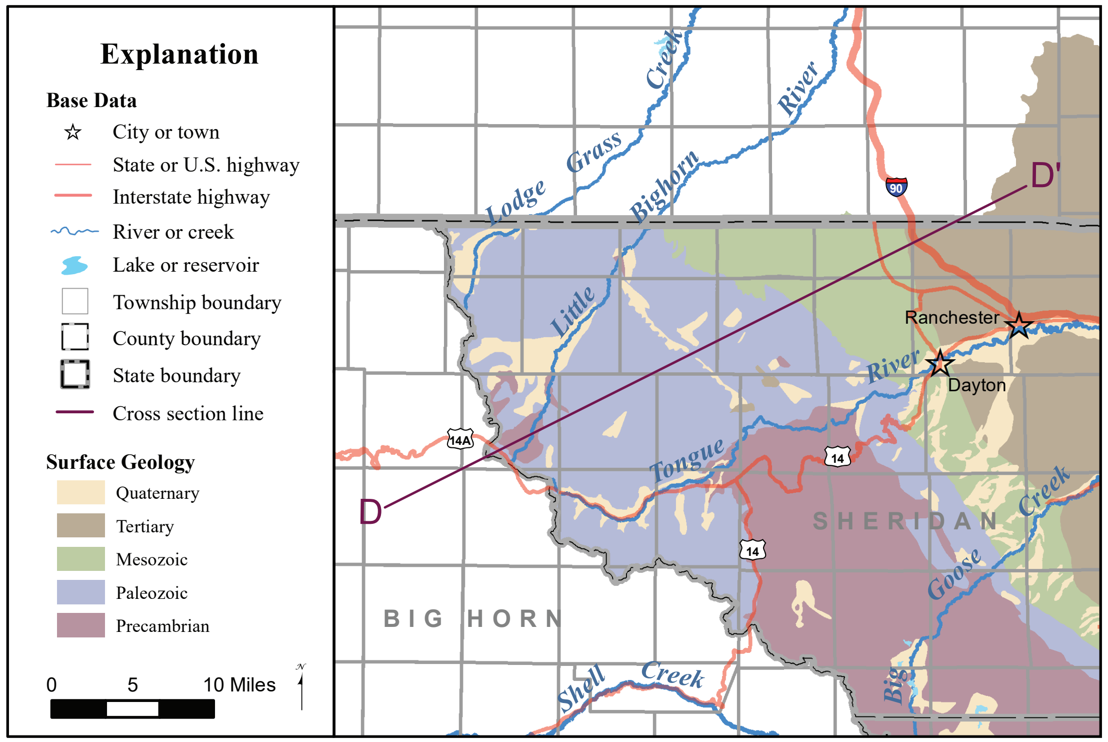
Lynds, R.M., 2013, Geologic storage assessment of carbon dioxide (CO_2) in the Laramide basins of Wyoming: Wyoming State Geological Survey Technical Memorandum 3, 200 p., 20 pls.

Figure 4-5. Geologic cross section C-C’.

Cross Section D-D’



Index Map and Line of Cross Section



Explanation

Symbols

——— Contact

Geologic Units

CENOZOIC–MESOZOIC
Tertiary–Cretaceous

Kpd	Parkman, Piney, and De Smet formations and Kinsbury Conglomerate

MESOZOIC
Cretaceous

Kp	Pierre Shale
Kc	Colorado shales

Cretaceous–Jurassic

Kcv	Cloverly-Sundance formations

Triassic

Ꞧ	Chugwater red beds

PALEOZOIC
Permian–Cambrian

Ct	Tensleep, Embar, and Amsden formations
Cm	Madison Limestone
O	Bighorn Dolomite
Є	Deadwood Formation

PRECAMBRIAN

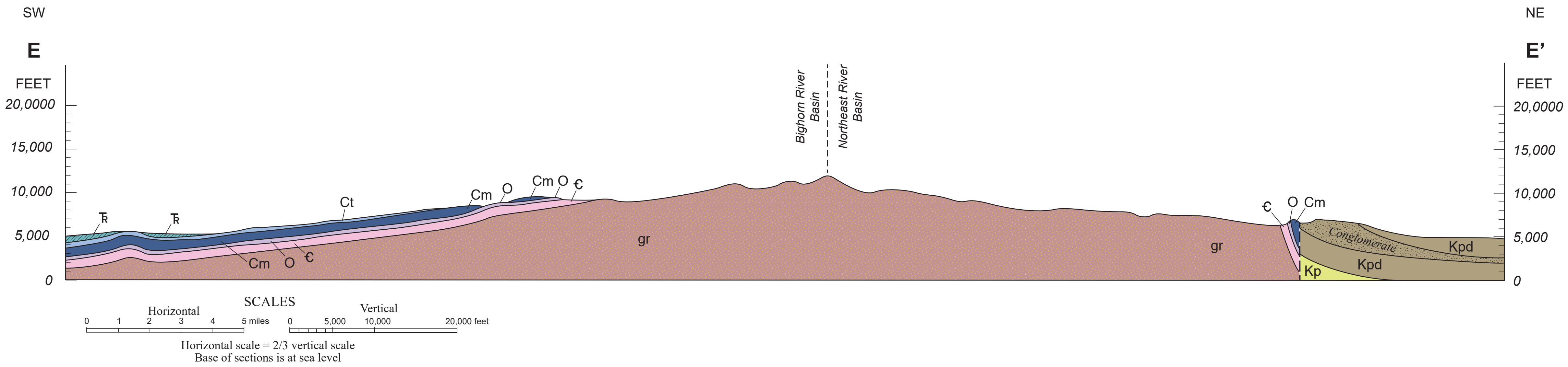
gr	Granite

Adapted from:

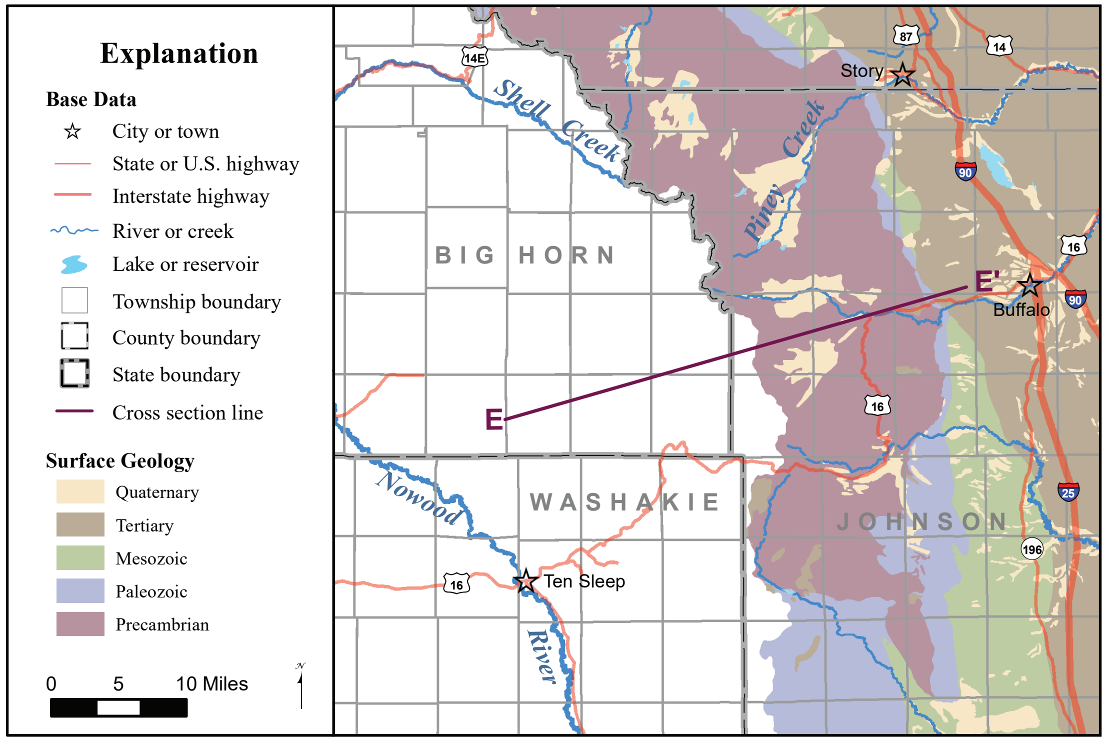
Darton, N.H., 1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 129 p., 5 maps, scale 1:125,000.

Figure 4-6. Geologic cross section D-D’. Stratigraphy does not match Love and others (1993)

Cross Section E-E’



Index Map and Line of Cross Section



Explanation

Symbols

—— Contact

—— — — Fault-dashed where approximately located

Geologic Units

CENOZOIC–MESOZOIC

Tertiary–Cretaceous

Kpd	Parkman, Piney, and De Smet formations and Kinsbury Conglomerate

MESOZOIC

Cretaceous

Kp	Pierre Shale

Triassic

Ꞧ	Chugwater red beds

PALEOZOIC

Permian–Cambrian

Ct	Tensleep, Embar, and Amsden formations
Cm	Madison Limestone
O	Bighorn Dolomite
Ꞓ	Deadwood Formation

PRECAMBRIAN

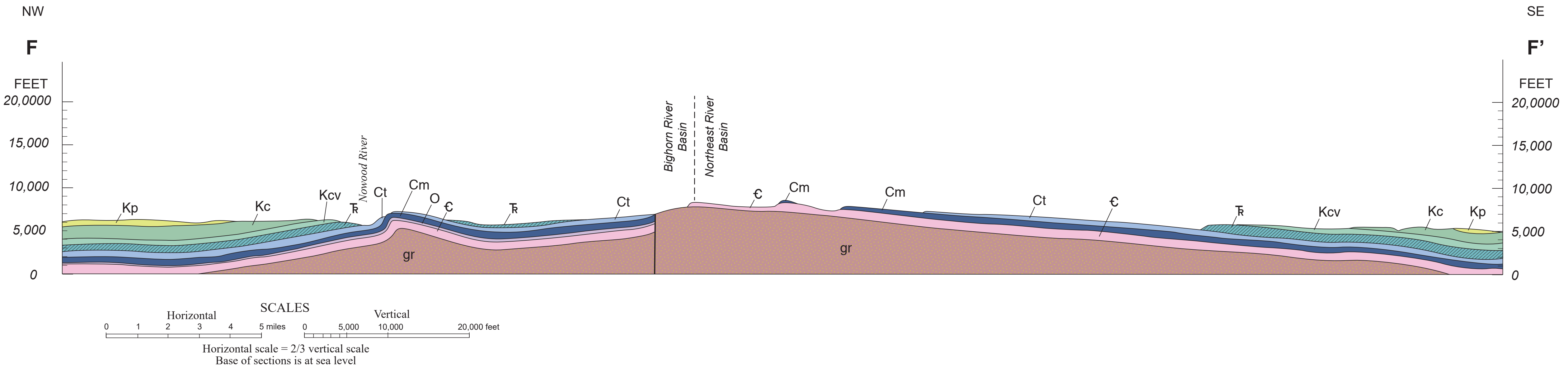
gr	Granite

Figure 4-7. Geologic cross section E-E’.

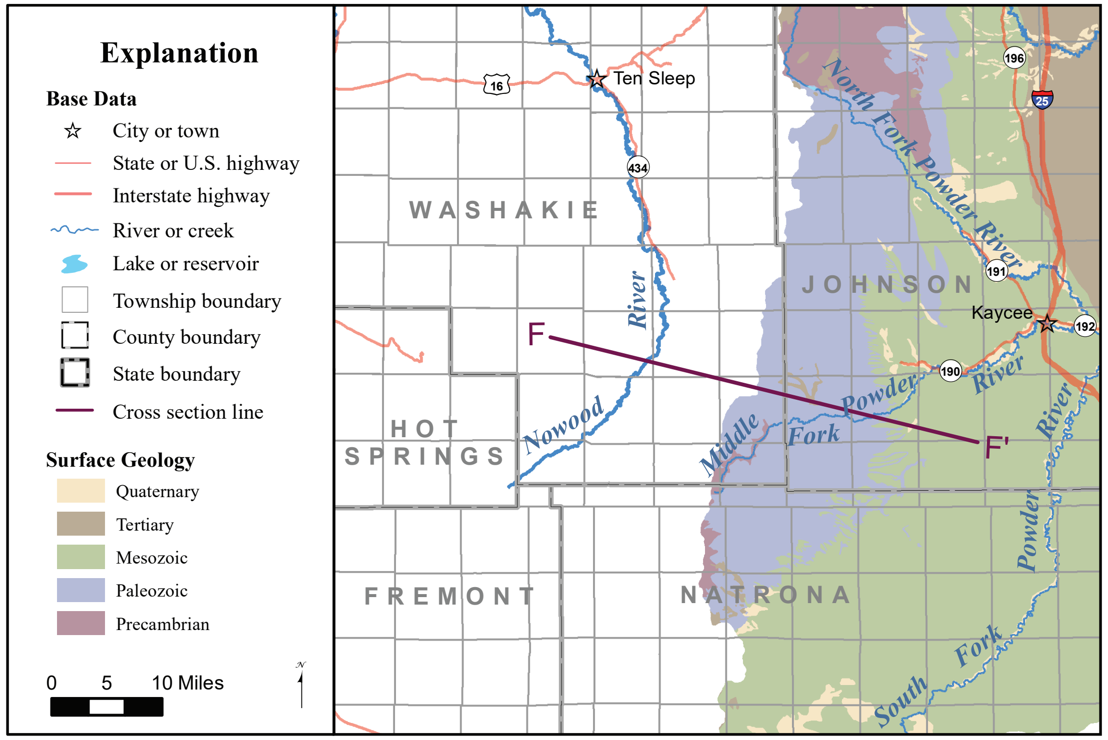
Adapted from:

Darton, N.H., 1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 129 p., 5 maps, scale 1:125,000.

Cross Section F-F’



Index Map and Line of Cross Section



Explanation

Symbols

Contact

Fault

Geologic Units

MESOZOIC

Cretaceous

Kp	Pierre Shale
Kc	Colorado shales

Cretaceous–Jurassic

Kcv	Cloverly-Sundance formations

Triassic

Ꞧ	Chugwater red beds

PALEOZOIC

Permian–Cambrian

Ct	Tensleep, Embar, and Amsden formations
Cm	Madison Limestone
O	Bighorn Dolomite
Ꞓ	Deadwood Formation

PRECAMBRIAN

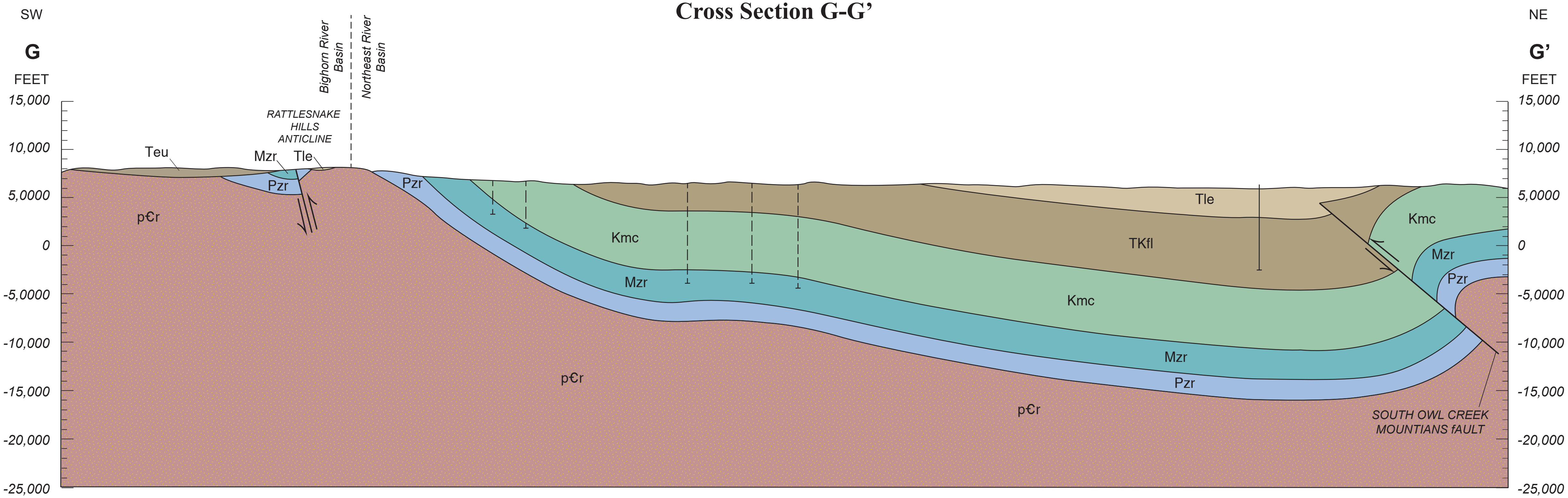
gr	Granite

Adapted from:

Darton, N.H., 1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 129 p., 5 maps, scale 1:125,000.

Figure 4-8. Geologic cross section F-F’.

Cross Section G-G’



Index Map and Line of Cross Section

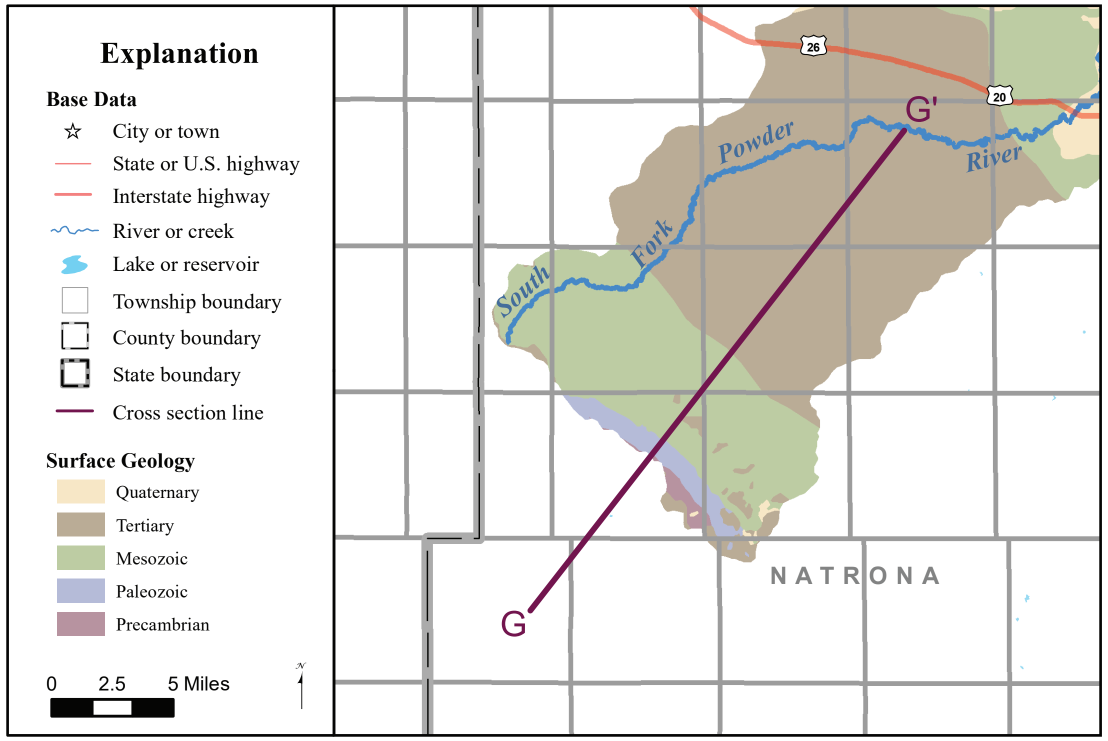


Figure 4-9. Geologic cross section G-G’.

Explanation

Symbols

Contact

Fault—arrows show sense of displacement

Well locations—solid if in line of section, dashed if projected into line of section

Geologic Units

NOTE: *Quaternary deposits not shown*

CENOZOIC
Tertiary

Teu	Lower Eocene and younger Tertiary rocks, undivided
Tle	Lower Eocene rocks

CENOZOIC–MESOZOIC
Tertiary–Cretaceous

TKfl	Fort Union and Lance formations

MESOZOIC
Cretaceous

Kmc	Meeteetse, Lewis, Mesaverde, and Cody formations
Mzr	Pre-Cody Mesozoic rocks

PALEOZOIC
Permian–Cambrian

Pzr	Paleozoic rocks

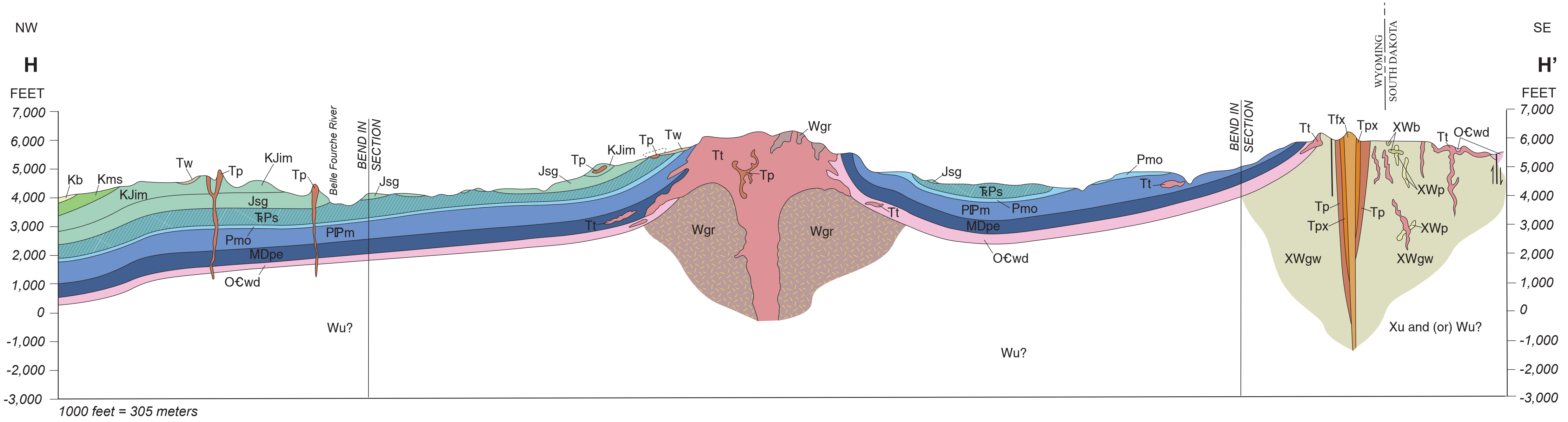
PRECAMBRIAN

p€r	Precambrian rocks

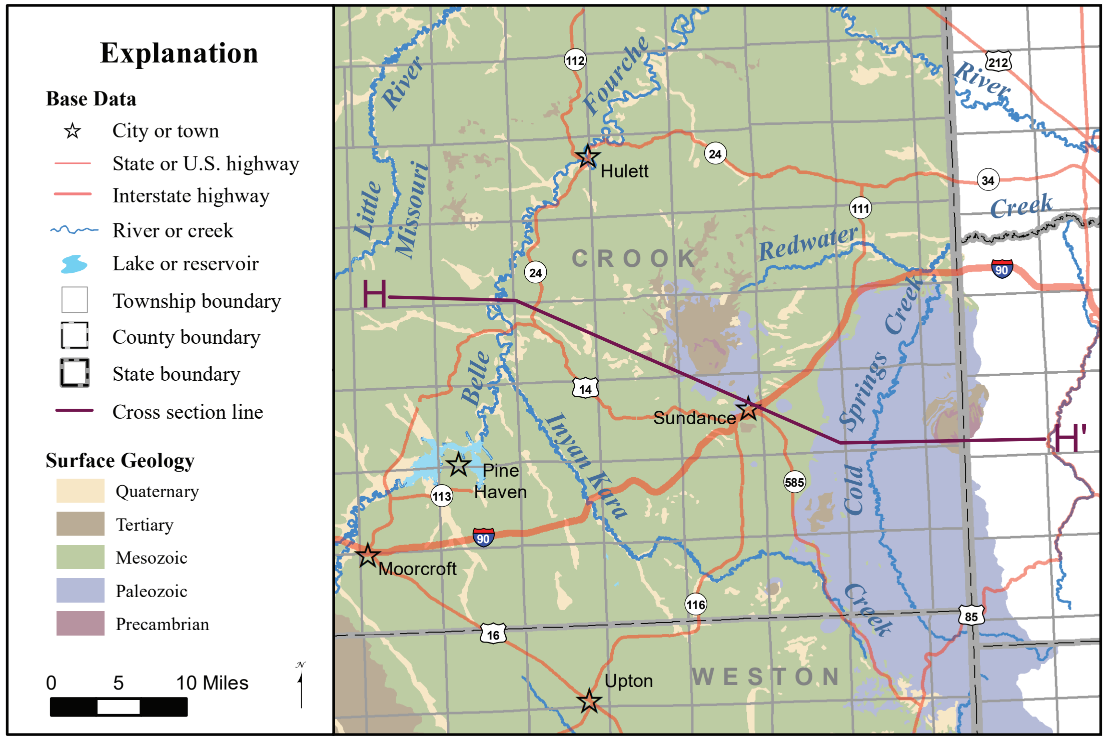
Adapted from:

Keefer, W.R., 1970, Structural geology of the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495, 35 p.

Cross Section H-H’



Index Map and Line of Cross Section



Explanation

Symbols

Contact
Fault—arrows show sense of displacement

Geologic Units

CENOZOIC
Tertiary

Tw	White River Group
Tp	Phonolitic intrusive rocks
Tt	Trachytic intrusive rocks
Tfx	Feldspathoidal breccia
Tpx	Pyroxenite

MESOZOIC
Cretaceous

Kb	Belle Fourche Shale
Kms	Mowry Shale, Newcastle Sandstone, and Skull Creek Shale

Cretaceous–Jurassic

KJim	Inyan Kara Group and Morrison Formation and Unkpapa Sandstone

Jurassic

Jsg	Sundance and Gypsum Spring formations

MESOZOIC–PALEOZOIC
Triassic–Permian

ŦPs	Spearfish Formation

PALEOZOIC
Permian

Pmo	Minnekahta Limestone and Opeche Shale

Permian–Pennsylvanian

PIPm	Minnelusa Formation

Mississippian–Devonian

MDpe	Pahasapa Limestone and Englewood Formation

Ordovician–Cambrian

OЄwd	Whitewood Dolomite, Winnipeg Formation, and Deadwood Formation

PRECAMBRIAN
Proterozoic

Xu	Undifferentiated Proterozoic rocks

Proterozoic–Archean

XWp	Pegmatite
XWb	Metabasalt
XWgw	Metagraywacke

Archean

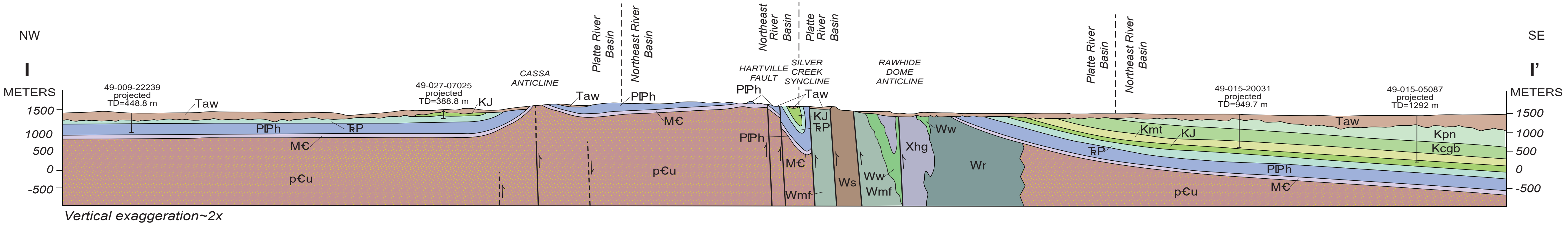
Wgr	Granite
Wu	Undifferentiated Archean rocks

Adapted from:

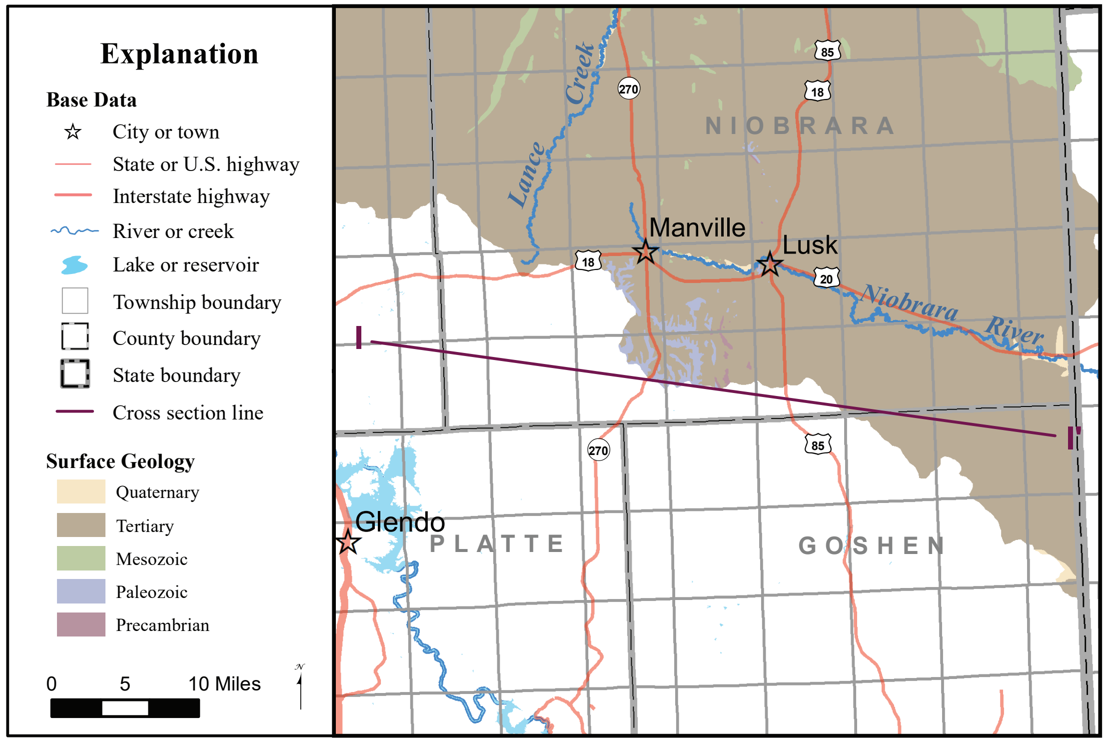
DeWitt, Ed, Redden, J.A., Buscher, D.P., and Wilson, A.B., 1989, Geologic map of the Black Hills area, South Dakota and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1910, scale 1:250,000.

Figure 4-10. Geologic cross section H-H’.

Cross Section I-I’



Index Map and Line of Cross Section



Explanation

Symbols

Contact

Fault—arrows show sense of displacement, and dashed where inferred

R-6
Well locations

Geologic Units

NOTE: *Quaternary deposits not shown*

CENOZOIC

Tertiary

Taw	Arikaree and White River formations, undivided

MESOZOIC

Cretaceous

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

Jurassic

KJ	Cloverly, Morrison,and Sundance formations, undivided

Triassic

ŦP	Chugwater and Goose Egg formations, undivided

PALEOZOIC

Permian–Pennsylvanian

PℙPh	Hartville Formation, undivided
MЄ	Mississippian, Devonian, and Cambrian (?) rocks, undifferentiated

PRECAMBRIAN

Proterozoic

Xhg	Gneissic phase of Haystack Range granite

Archean

Wr	Rawhide Buttes Granite
Ww	Wildcat Hills Formation
Ws	Silver Springs Formation
Wmf	Mother Featherlegs Metabasalt
pЄu	Precambrian rocks, undifferentiated

Adapted from:

McLaughlin, J.F., Stafford, J.E., and Harris, R.E., 2011, Geologic map of the Lusk 30’ x 60’ quadrangle, Niobrara, Goshen, Converse, and Platte counties, Wyoming, and Sioux County, Nebraska: Wyoming State Geological Survey Map Series 82, scale 1:100,000.

Figure 4-11. Geologic cross section I-I’.

Chapter 5

Technical concepts: Hydrogeology and groundwater quality

Karl G. Taboga, Timothy T. Bartos,
James E. Stafford, Laura L. Hallberg,
and Melanie L. Clark

This chapter briefly discusses the technical concepts and terminology used in this groundwater study. Comprehensive descriptions of the basic concepts of hydrogeology can be found in U.S. Geological Survey (USGS) Water Supply Paper 2220 (Heath, 1983), available on the USGS publications website.

Hydrogeology is the area of geology that studies the occurrence, distribution, and movement of groundwater through the bedrock and unconsolidated material (such as soils) that form the earth's crust. In contrast, the term geohydrology, which is often used interchangeably, more properly describes a branch of engineering that studies subsurface fluids. Groundwater hydrology is defined by the USGS as the branch of hydrology concerned with the occurrence, movement, and chemistry of groundwater. The study of groundwater resources is an interdisciplinary field that requires knowledge of geology along with an understanding of the basic principles of physics, chemistry, mathematics, biology, and engineering. The hydrogeologist must be able to understand the physical and chemical interactions that occur between groundwater, host rock units, unconsolidated materials, minerals, and the surface environment.

Hydrogeologists usually study groundwater resources that are economically accessible and can be directly used for the benefit of society. Shallow groundwater resources (e.g., water table and shallow, confined aquifers) and their interactions with surface waters are of interest to geologists, water managers, soil scientists, agriculturalists, hydrologists, water law attorneys, civil engineers, and citizens who use these resources for their water supplies. Groundwater in deeper formations may be uneconomic to produce or, more commonly, of poor quality, unsuitable for domestic or agricultural uses. The hydrogeology of these deeper formations is still important to mineral and petroleum resource geologists, geophysicists, and petroleum engineers. The suitability of groundwater for a particular beneficial use depends primarily on water quality. In this study, groundwater quality is evaluated relative to its suitability for domestic, irrigation, and livestock use, based on the Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA) and the Wyoming Department of Environmental Quality's (WDEQ) class-of-use, water quality standards (sec. 5.5.1; chap. 7). This chapter also examines aquifer sensitivity, potential sources of groundwater, and state and federal programs designed to characterize and protect groundwater quality in Wyoming.

5.1 DEFINITIONS AND CONCEPTS

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

5.1.1 Definitions

The technical terms defined in this section provide the reader with the basic terminology needed to understand the information presented in this report. A more complete glossary of hydrogeological terms (Sharp, 2007) is available at: http://www.geo.utexas.edu/faculty/jmsharp/sharp-glossary.pdf.

Geologic unit—a geologic formation, member, lens, tongue, bed, flow, other stratigraphic unit, or group of rocks that have been correlated, named, and mapped by geologists based on lithological and geospatial continuity and other properties. The WSGS website (http://www.wsgs.wyo.gov) contains a generalized stratigraphic chart and a map of Wyoming's geologic units (Love and Christiansen, 1985). The WSGS also provides Geographic Information Systems (GIS), datasets of Wyoming bedrock, and surficial geology at http://www.wsgs.wyo.gov/pubs-maps/gis. Additionally, the USGS Geolex website, https://ngmdb.usgs.gov/Geolex/search, contains extensive information on geologic units in all states.

Lithostratigraphic unit—a mappable stratigraphic unit defined by lithologic uniformity and continuity. Lithostratigraphic and, to a lesser degree, other stratigraphic units are the most commonly characterized components of geologic units and are generally used in geologic mapping where allowed by the map scale. Section 5.2 of this study provides an additional discussion of lithostratigraphic units.

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

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

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

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

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

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

Unconfined aquifer—the water-saturated part of a hydrogeologic unit that contains groundwater under atmospheric pressure and thus rises and falls relatively quickly in response to recharge (e.g., precipitation, irrigation, or waste disposal) and changes in atmospheric pressure. Unconfined aquifers are generally saturated only in the lower part of the host hydrogeologic unit.

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

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

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

Colluvium—Loose, unconsolidated earth materials deposited primarily by gravity at the foot of a hillslope including talus and cliff debris.

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

Potentiometric surface—a surface that represents the total head in an aquifer. Within an unconfined aquifer, the potentiometric surface is an actual, physical surface. In a confined aquifer, the potentiometric surface is a conceptual surface defined by the level to which water rises in wells that penetrate that aquifer. Potentiometric surface has generally replaced the older terms piezometric surface and water table, and groundwater surface is a more current synonym. Potentiometric surfaces are typically mapped as equal-elevation contours in feet above mean sea level.

Water table—the groundwater surface within an unconfined aquifer under atmospheric pressure. The water table is the surface where pore-water pressure equals atmospheric pressure. While the capillary fringe above the water table is saturated, it is below atmospheric pressure and thus fails to meet the definition of the water table. In most settings, the water table is not a flat, horizontal surface, but is contoured like the land surface above. In colloquial usage, the water table is the first occurrence of unconfined groundwater encountered at depth and is generally equivalent to groundwater surface or potentiometric surface.

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

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

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

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

Static head or static water level—the level of water in a well when neither the well nor surrounding wells are being pumped and the total head in the aquifer is generally at equilibrium. Static head is usually expressed in feet of elevation above mean sea level; water levels are typically described in terms of depth (feet or meters) below ground surface (bgs).

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

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

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

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

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

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

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

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

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

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

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

Specific yield—the drainable porosity of an unconfined aquifer, reported as a ratio of the volume of water that will drain under gravity to the volume of saturated earth material. Specific yield is a dimensionless parameter that describes the volumetric proportion of aquifer material that provides water. Specific yield, porosity, and effective porosity are all dimensionless properties, but when multiplied by the volume of the saturated rock, porosity will equal total void space, effective porosity will return total groundwater volume, and specific yield will return the volume of available groundwater (sec. 5.1.4).

Storage coefficient—the volume of water released from or taken into storage per unit surface area of the aquifer, per unit change in total head. Storage coefficient is a dimensionless parameter—the units in the numerator and denominator cancel. In an unconfined aquifer, the water released from storage is from gravity drainage and the storage coefficient is essentially equivalent to specific yield. In confined aquifers, water released from storage comes primarily from the expansion of the water and the compression of aquifer materials as pressure is relieved during pumping. Because these release small volumes of water from storage, the storage coefficients of confined aquifers (10-5 to 10-3) are generally several orders of magnitude smaller than unconfined aquifers (0.1 to 0.3).

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

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

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

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

Losing stream—a surface water stream or part of a stream that recharges the underlying or adjacent hydrogeologic unit(s), resulting in decreased downstream flow.

Total dissolved solids (TDS)—a measure of the total concentration of minerals dissolved in groundwater, generally expressed in either milligrams per liter (mg/L) or parts per million (ppm). Generally, these means of measuring are equivalent.

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

5.1.2 Types of groundwater flow

Groundwater flow occurs as porous flow, conduit flow, fracture flow, or some combination of these three types.

- Porous flow occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone, or unconsolidated deposits) or through intercrystalline pore spaces within igneous or metamorphic rocks. The size of the sediment grains or mineral crystals affects porous flow. Larger open pores between larger grains (or crystals) are generally more conducive to flow than smaller grains/pores. In an aquifer with a wide range of grain sizes (poorly sorted), the fine-grained material fills in the larger pore spaces and reduces flow toward that of a fine-grained aquifer. Porous flow is also referred to as primary porosity, i.e., the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the rock matrix.

- Conduit flow occurs through large, discrete openings (pipes, cavities, channels, caverns, and other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite, or halite. Conduits form by the dissolution of soluble minerals in bedrock or by subsurface sediment transport (piping) through unconsolidated or loosely consolidated material.

- Fracture flow occurs through interconnected partings in bedrock: fractures and joints developed during structural deformation (folding, faulting), expansion (rapid overburden erosion) or compaction (rapid deposition), physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation), or thermal contraction (fractured and columnar basalts). Fractures occur either along or across existing bedding planes or other types of geologic contacts. The porosity of conduits and fractures is referred to as secondary porosity, although, frequently, conduits and fractures within a unit can transport water several times faster than the primary porosity in many aquifers.

5.1.3 Groundwater recharge, discharge, and flow

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

5.1.3.1 Groundwater recharge

The accumulation of groundwater within an aquifer requires, first, a source of water. In shallow aquifers, that source is ultimately precipitation. Initially, precipitation will infiltrate at the ground surface, percolate through the unsaturated (vadose) zone, and enter the water table. This process alone can take days to hundreds of years before the precipitation enters a receiving aquifer as "recharge." The path groundwater travels from there, however, can be complicated further by moving between aquifers and confining units depending on the flowpaths within a particular system. Understanding the sources, amount, and delivery timing of recharge is essential to characterize any groundwater resource. Despite its importance, recharge is one of the most difficult parameters to quantify. Recharge cannot be measured directly, but is estimated indirectly using tools such as chemical or heat tracers, water budget calculations, or groundwater level analyses (Healy and Scanlon, 2010).

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (fig. 5-1) and serve as significant sources of recharge. Consequently, the most important recharge areas in Wyoming are hydraulically connected with sources of mountain precipitation. Especially valuable is recharge that infiltrates alluvial materials and bedrock outcrops that border the mountain ranges (mountain front recharge), and the thick alluvial deposits underlying stream channels that receive a large proportion of their flows from mountain discharges. Recharge storage in Wyoming builds as snowpack accumulation during late fall, winter, and early spring when seasonal precipitation is higher and cool daily mean temperatures prevent melting. Recharge rates are highest in late spring and the earliest part of summer during and following snowmelt. During those times, vegetation is still in a quasi-dormant state, rates of evapotranspiration are relatively low, and soils have newly thawed. The melting snowpack maximizes contact with the ground surface and enhances the duration and rate of infiltration.

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

During a precipitation event, vegetation intercepts some of the moisture before it reaches the ground surface. This water, called canopy storage, will later be lost to evaporation or fall to the ground. Precipitation that reaches the surface will infiltrate into the ground if the infiltration capacity of the soil has not been exceeded. Initially, infiltrating water will replace any depletion in soil moisture, and then the remaining infiltrating water will percolate downward under the force of gravity through the unsaturated zone to the water table. The hydraulic characteristics and antecedent moisture conditions of the unsaturated zone affect the amount and speed of the infiltrating water that reaches the water table. If the infiltration capacity of the soil is exceeded, water flows overland to be stored on the surface in puddles (depression storage) or to discharge to streams. In the latter case, some of the overland flow may infiltrate the streambed and enter the receiving aquifer as recharge downstream from the site of precipitation. A general estimation is that approximately 10 percent of precipitation recharges groundwater.

The description given above is a simplification of the infiltration process. In fact, infiltration rates can vary widely and are affected by multiple factors:

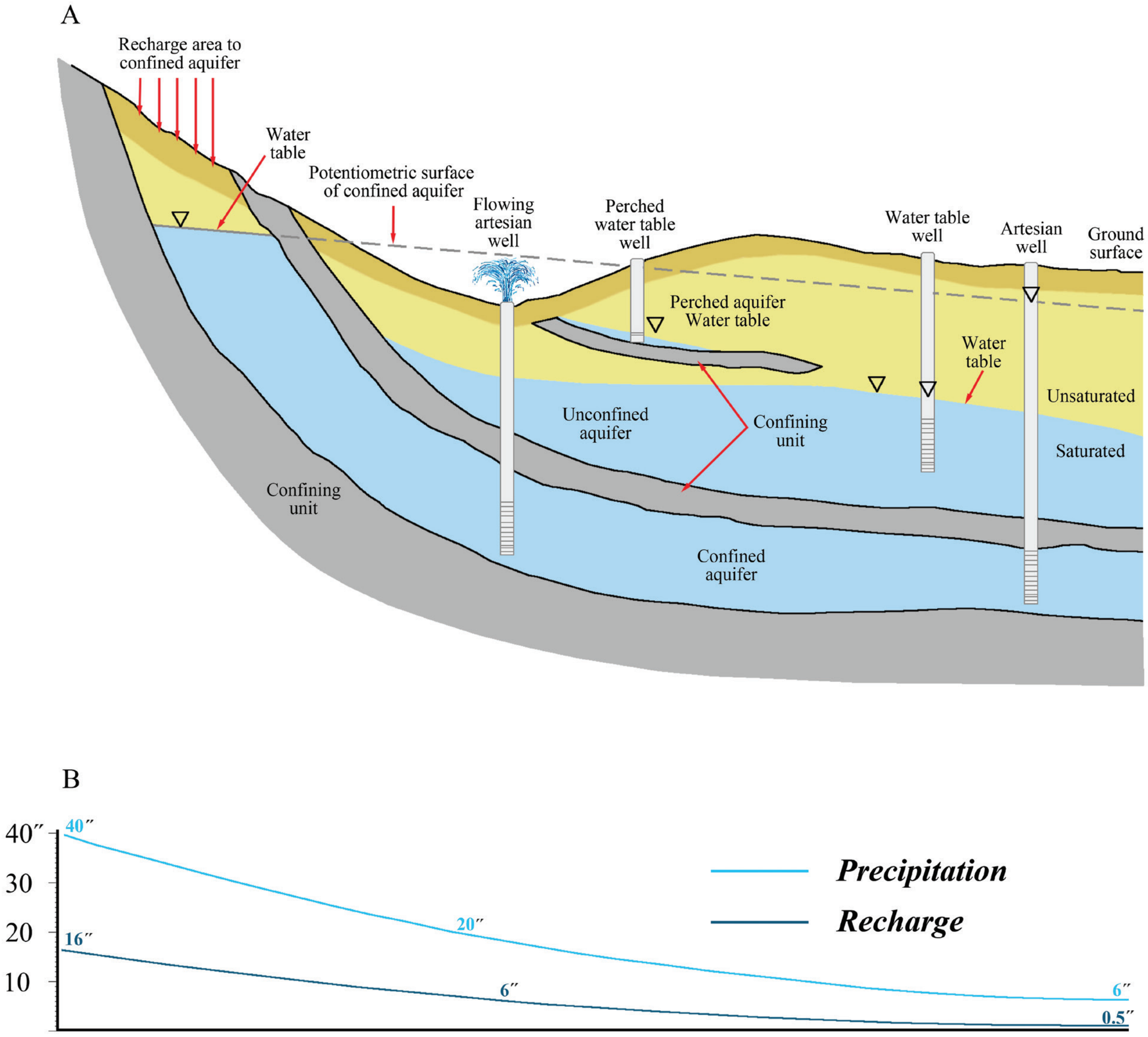


Figure 5-1. (A) Conceptual cross section of typical groundwater features that occur in a typical Rocky Mountain laramide structural basins and synclinal features of the Thrust Belt. Older hydrogeologic units outcrop and recharge at margins, dip steeply (basinward), and become confined within short distances.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

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

In addition to infiltration from the surface, an aquifer may also receive recharge as leakage from adjacent confining units. Although recharge may flow very slowly from confining unit to receiving aquifer, the volume of leakage can be quite substantial over time provided the geospatial contact area between the two units is large.

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

While several methods have been described for estimating recharge (Healy and Scanlon, 2010), direct measurement of recharge is problematic due to the high degree of geospatial and temporal variability of precipitation and the numerous factors that affect infiltration. In 1998, the Spatial Data and Visualization Center (SDVC) at the University of Wyoming conducted a statewide recharge evaluation using geospatial analysis (Hamerlinck and Arneson, 1998). Originally, the SDVC calculated average annual recharge for the 1961–1990 period of record by:

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

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

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

This study used a WSGS empirical model (Taboga and Stafford, 2016) to estimate average annual recharge in the Wyoming portion of the NERB (chap. 6) for the 30-year period of record from 1981–2010 (fig. 5-2; tables 6-1 – 6-3).

5.1.3.2 Groundwater discharge

Natural discharges of groundwater occur in many ways. In Wyoming basins, the most common modes of discharge include leakage into adjacent geologic units, flow from springs, subsurface seepage (baseflow) into streams, wetlands, lakes, and other surface waters, and direct evaporation where the water table is shallow enough that capillarity or plant transpiration brings groundwater to the surface (evapotranspiration). Like recharge, the magnitude of total natural discharge is difficult to determine, especially on a basin-wide basis. While some forms of discharge, such as visible surface flows from springs, are readily measured, others are difficult to quantify because they are concealed (leakage between geologic units, subsurface flows in streambeds—i.e., hyporheic flows—or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). Discharges that cannot be measured directly must be estimated through proxy calculations. For example, using a mass balance

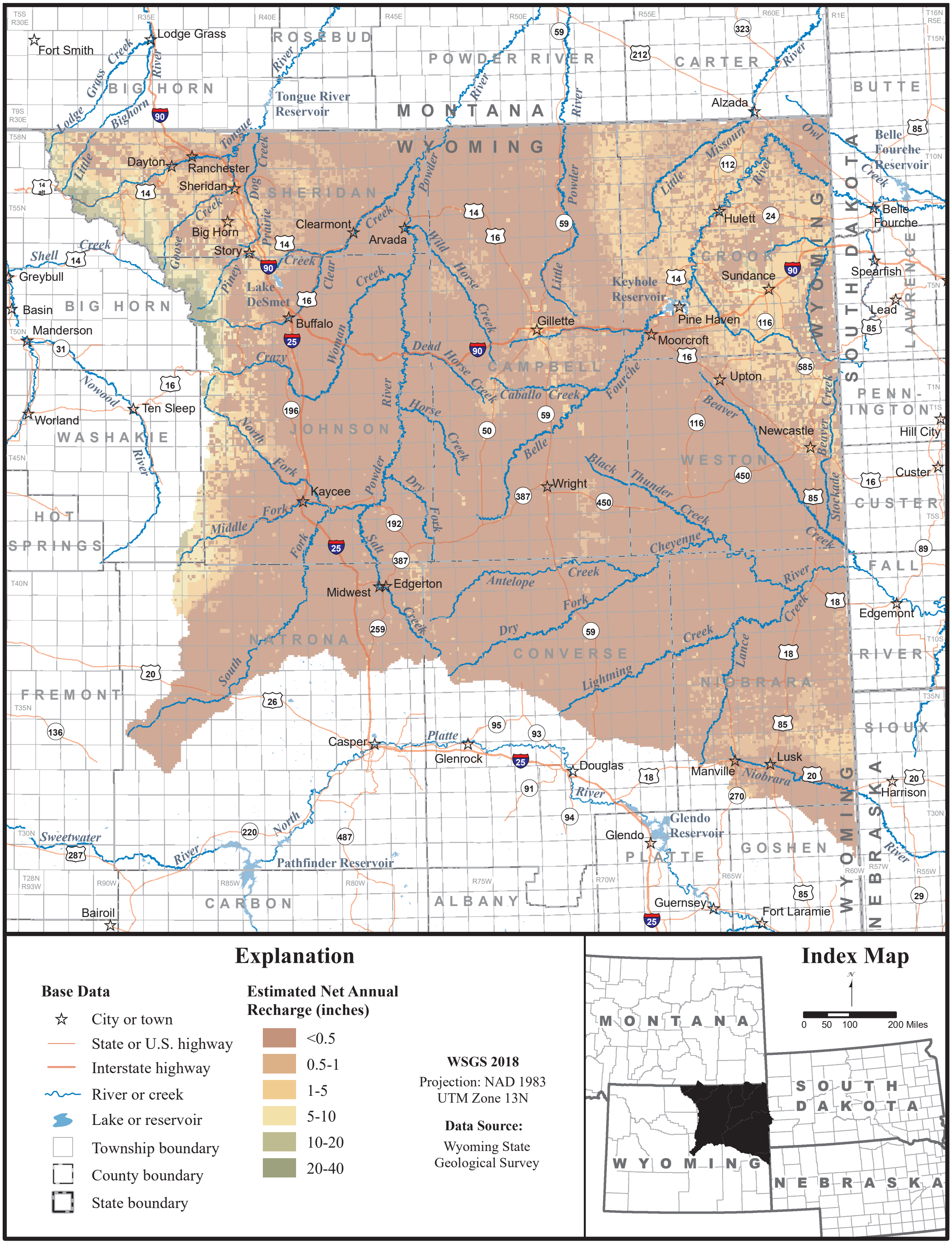


Figure 5-2. Estimated net annual aquifer recharge, in inches, NERB, Wyoming.

(water balance) model can refine estimates when information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available, as is the case in this study (chap. 8).

In addition to withdrawals from wells, artificial avenues of groundwater discharge include seepage into mines and other excavations, discharges into irrigation and drainage canals, and flow between aquifers in poorly completed wells. Groundwater withdrawals for beneficial use are estimated in previous water plans (HKM Engineering and others, 2002a, b) and are discussed in chapter 8.

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

5.1.3.3 Groundwater flow

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

Although groundwater flow is driven by gravity, water does not always flow downward, but from areas of higher hydraulic pressure to areas of lower hydraulic pressure. In the deeper subsurface, groundwater can flow from a lower to a higher elevation, as observed at artesian wells (fig. 5-1) and some springs that discharge groundwater from deep aquifers. Groundwater will flow in the directions indicated on potentiometric surface maps if permeable pathways exist; however, flow along preferential pathways (e.g., fractures and faults) can depart from the direction of maximum gradient. Hydraulic gradients are commonly steep in low permeability geologic units where there is substantial resistance (friction) to flow. Conversely, high-permeability units, where friction is low, generally exhibit low hydraulic gradients. The slope (gradient) of a potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where the resistance to flow in any direction is negligible and the gradient is virtually flat.

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

Groundwater occurs under unconfined (water table) conditions in unconsolidated deposits and bedrock formation outcrop areas throughout the NERB. In shallow, unconfined aquifers, recharge, flow, and discharge are predominantly controlled by topography, vegetation, and stream drainage patterns. The water table of an unconfined aquifer is recharged by precipitation and generally reflects the overlying topography, especially in areas of high relief. Groundwater from unconfined aquifers can discharge to the surface at springs where the elevation of the water table is greater than the surface elevation. Complex interactions can occur among bedrock aquifers, unconsolidated aquifers, and surface waters, especially along drainages lined with alluvial deposits.

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

Confined groundwater flow within the deeper bedrock formations of the NERB is primarily controlled by structure and stratigraphy. Major aquifers and aquifer systems in the NERB, such as the Wasatch-Fort Union aquifer, occur predominantly within interstratified sequences of high- and low-permeability sedimentary strata (Flores and others, 2010). Such aquifers are commonly heterogeneous and anisotropic on both local and regional scales. Deeper groundwater flow in the NERB is predominantly through permeable formations down-gradient from higher to lower hydraulic pressure. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage, safe yield, and sustainable development

In addition to functioning as the conveyance system for groundwater flow, the saturated geologic units that compose the aquifers of the NERB also store enormous volumes of groundwater. Modern groundwater projects seek to develop the targeted water resource in a sustainable manner without depleting storage and natural discharges to unacceptable levels. This section discusses the basic technical concepts of groundwater storage, "safe yield" and "sustainable yield."

Groundwater resource assessments consider both the total volume of groundwater present in an aquifer and the fraction of that volume available for development at acceptable costs. In the early stages of a project, the three primary factors that decide how much of the groundwater contained within an aquifer will be economically producible are development costs, the status of existing water rights, and water quality requirements. Groundwater must be of suitable quality to satisfy the requirements for its intended use and treatment facilities are costly to build and operate. Section 5.5 and chapter 7 discuss groundwater quality in the NERB.

Hydraulic properties, dependent on an aquifer's effective porosity (sec. 5.1.1) and storage coefficient, determine the amount of water that an aquifer will yield to natural drainage or to pumping. Both of these properties are important to consider when designing a sustainable groundwater development project.

5.1.4.1 Groundwater storage

The storage coefficient is the amount of water that a unit volume of an aquifer will release from (or take into) storage per unit change in hydraulic head, expressed as a percentage or decimal fraction. Storage coefficient applies to both confined and unconfined aquifers.

Specific yield applies to unconfined aquifers. Specific yield is the fraction of water that a saturated unit volume of rock will yield by gravity drainage. Specific yield is expressed as a percent (or decimal fraction) of the unit volume. In an unconfined aquifer, specific yield is essentially the same as effective porosity. Specific retention, also expressed as a percent (or decimal fraction) of the unit volume, is the volume of water that remains in the unit volume of rock after drainage, in isolated pores and attached to the aquifer matrix by molecular attraction and surface tension. Finer-grained aquifers in general have higher specific retentions than coarser-grained aquifers even though finer-grained materials may have higher total porosity than coarser-grained materials. For example, after drainage, a larger fraction of the total water is retained in a cubic foot of fine sand than in a cubic foot of river cobbles. The sum of specific retention and specific yield is equal to porosity. Highly productive unconfined aquifers typically exhibit high specific yields.

The mechanisms of groundwater release in unconfined and confined aquifers vary greatly. In an unconfined aquifer, water drains by gravity and hydraulic head declines. In contrast, the groundwater released from a confined aquifer comes from specific storage, that is, the volumetric expansion of groundwater and the compression of the aquifer matrix as water pressure decreases from pumping. Because the volume of water that is produced due to these elastic properties (specific storage) is negligible in an unconfined aquifer, the storage coefficient in an unconfined aquifer is essentially equal to specific yield. Conversely, specific yield cannot be determined for a confined aquifer unless the water level (hydraulic head) is reduced to the point that the aquifer becomes unconfined, after which the storage coefficient is essentially equal to the specific yield.

To some extent, the groundwater stored in an aquifer can operate as a buffer between recharge, natural discharge, and withdrawals, allowing relatively constant production of groundwater during periods of variable recharge. Enormous volumes of water can be released from storage in a geospatially large aquifer from relatively small persistent declines in hydraulic head, allowing continual withdrawal through periods of deficient recharge. Large declines in hydraulic head from over-pumping, however, can reduce aquifer water levels to the point where recharge is induced, turning gaining streams into losing streams or drying up spring flows (Barlow and Leake, 2012). Because of the difference in how water is released from storage, specific yield in unconfined aquifers is generally orders of magnitude larger than the specific storage of confined aquifers. Thus, unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than do confined aquifers. Unconfined aquifers are therefore generally more attractive prospects for development. Properly managed, groundwater is one of society's most important renewable resources; however, over pumping can result in a long-term and perhaps irreversible loss of sustainability through storage depletion and compression of the aquifer material.

5.1.4.2 Safe yield

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

The concept was subsequently applied to groundwater resources. Lee (1915) first described safe yield as, "the limit to quantity of water that can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Lee noted that safe yield "… is less than indicated by the rate of recharge, the quantity depending on the extent to which soil evaporation and transpiration can be eliminated from the region of groundwater outlet." Meinzer (1923) placed it within the context of economics when he defined safe yield as ". . . the rate at which ground water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." However, it is now recognized that ownership, legal, financial, and environmental issues, the potential for aquifer damage, and interference with the development of other resources must also be considered in evaluating safe yield for groundwater development. The definition given by Fetter (2001) includes these factors,

> "The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head by pumping."

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

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

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

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

In the past, when it was thought that the upper limit of an aquifer's safe yield was determined by the amount of annual recharge, the sustainability of groundwater development was frequently analyzed by a conservation of mass approach variously referred to as a water balance, hydrologic budget, or water budget. The fundamental expression for this type of analysis as applied to groundwater resources is:

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

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

Average annual recharge rates for the NERB estimated by the WSGS (Taboga and Stafford, 2016), are presented in figure 5-2. Annual recharge to specific groups of aquifers is estimated and discussed in section 6.2. A water balance for the NERB was prepared for this study (chap. 8) using information provided in previous NERB Water Plans (HKM Engineering and others, 2002a, b) and additional information developed by the WSGS. The aquifer-specific recharge estimates contained in chapter 6 of this study were integrated into the water balance, which should be used to:

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

In practice, a unique and constant value of safe yield cannot be calculated accurately on the basin scale due to a number of limiting physical and temporal factors:

- Drainage basins are not homogeneous underground reservoirs, rather, they are complex systems of aquifers and confining units that possess high levels of geological and hydrological heterogeneity. For example, a large drainage basin like the Platte River (Taucher and others, 2013) may contain several structural basins, wholly or in part. Because of these complexities, the understanding of key factors such as basin geometry and structure, hydraulic relationships between basin hydrogeological units, and deep basin hydrodynamics is largely absent within a regional model.
- Aspects of spatial scale must be considered. An analysis of total groundwater uses over a regional scale, such as a river basin, may indicate that groundwater withdrawals constitute a small percentage of calculated annual recharge and imply that water resources are not over-utilized. A regional analysis may, however, conceal local scale groundwater storage depletions that have become problematic. Again, in the case of the Platte River Basin (Taucher and others, 2013), a basin wide water balance determined that recent annual consumptive uses of groundwater constitute about 13 percent of mean annual recharge. From this analysis, a safe yield evaluation would conclude that groundwater storage levels in the basin are relatively secure. In fact, some areas of the High Plains aquifer in Laramie County, Wyoming, have seen groundwater level declines of 25 to 50 feet since 1950 (McGuire, 2013).
- Sufficient datasets required to make such estimations have not been developed in most drainage basins for a number of reasons. First is the expense of collecting adequate hydrogeologic data from a representative sample set. The problem is further exacerbated in lightly populated rural areas where groundwater wells are sparsely distributed. There, adjacent sampling points (wells) are frequently separated by miles of unpaved roads, inaccessible during winter and early spring months. Second, wells are most likely sited in hydrogeologic units where the probability of successful completion is highest. Thus, the available hydrogeologic data is skewed toward over-represented productive areas and away from less productive units where few wells are drilled. For example, in the Bear River Basin of southwestern Wyoming, 65 percent of likely producing wells of all types are sited on Quaternary Alluvial units, which comprise 20 percent of basin surface area. The remaining wells (35 percent) are sited in bedrock aquifers (Taboga and others, 2015).
- Hydrologic inputs (recharge) and outputs (discharges) are not delivered instantaneously and, in most cases, have not been accurately measured. Similarly, changes in storage are dependent on aquifer response times that can range from days to hundreds of years (Sophocleous, 2005). Thus, currently observed changes in storage may reflect present day discharges superimposed on recharge levels from decades past. In such cases, water man-

agers must be careful to avoid evaluating current aquifer storage volumes relative to recent precipitation rates given the long lag times of some aquifers and the cyclic nature of drought in the semi-arid west.

5.1.4.3 Sustainable development

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

The American Society of Civil Engineers (ASCE, 1998) defines sustainable water systems as, "those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." The list of factors that affect the planning and development objectives of any water resource system is extensive. Water planners are required to consider current and future water demands, population, land use, climate, public opinion, water resource utilization, technology, and hydrologic science. Given the uncertainties encountered in these analyses, it is likely that no constant single value of sustainable yield can be developed for a particular project. The determination of sustainable yield is not a single set of calculations, but a process that requires periodic re-evaluation as design elements change with time (Maimone, 2004).

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

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

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

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

5.2 MAP/ROCK UNITS: GEOLOGIC, STRATIGRAPHIC, AND HYDROGEOLOGIC

The assemblage of rocks and other geologic elements that compose groundwater basins, their hydrologic properties, and stratigraphic and structural interrelationships, form the geologic framework for groundwater recharge, storage, and flow. Geologic units are distinct, mappable units that have been defined in geologic literature. Geologic units are designated using a wide range of criteria that include appearance (lithology), microscopic examination (petrography), the presence of certain fossils (paleontology), the time of formation (chronostratigraphy), and geochemistry. Geologic units are categorized in a hierarchical manner based on size and complexity. In descending order of hierarchy, these categories are supergroup, group, formation, member, and bed.

The North American Stratigraphic Code (NASC, 2005) describes the procedures used to define, classify, and name geologic units. Interested readers can access the code online at: http://www.nacstrat.org/north-american-stratigraphic-code.

The USGS Geologic Map of Wyoming (Love and Christiansen, 1985) was used extensively in this study. The map shows distinguishable bodies of rocks as "map units," which are mapped geologic units. Sheet 2 describes the geographic and chronological distribution of both the map units and their component stratigraphic units, and contains stratigraphic correlation diagrams. Love and others (1993) correlates the stratigraphic units shown on the 1985 map explanation developed from the individual 1° x 2° (1:250,000 scale) geologic quadrangle maps covering the state, and includes revisions subsequent to the 1985 map. The USGS and the WSGS compiled the map units in Love and Christiansen (1985) into a digital database of GIS, which was used to develop plate 1 (surface geology), plate 2 (surface hydrogeology), and the hydrostratigraphic chart in figures 7-2 and 7-8.

The geologic units mapped on plate 1 are described in appendix A. The hydraulic, physical, and hydrogeochemical characteristics of individual stratigraphic units are discussed in detail in chapter 7. The USGS developed the hydrostratigraphic charts shown on figures 7-2 and 7-8 following extensive review of previous studies. Finally, plate 2 maps exposures of these hydrostratigraphic units in the NERB.

Determining the hydrostratigraphy of a geographic area is not a simple matter, especially in Wyoming's complex geological settings. Hydrogeologic units can be composed of multiple geologic and/or rock units, or just portions of these units. The units that compose an aquifer or aquifer system in one area may be considered differently in places where the same units have different hydrologic properties or are composed of different sub-units.

5.3 WYOMING STATEWIDE AQUIFER CLASSIFICATION SYSTEM

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

Major aquifer (alluvial)—The highly permeable, unconsolidated, flat-lying sand and gravel deposits that compose the alluvium located along rivers and streams are some of the most productive aquifers in the state and the NERB. Under favorable conditions, these aquifers can provide well yields of 500 to 2,000 gallons per minute (gpm). Yields are generally lower where the deposits are either thin, contain abundant fine-grained material, occur at higher elevations, or are hydrologically isolated from active streams (e.g., terrace deposits). Flow through unconsolidated material occurs through primary (intergranular) porosity. Where the alluvial aquifer is hydraulically connected with an active stream, direct infiltration from the stream provides most of the groundwater in storage, and alluvial-aquifer water quality reflects the water quality of the stream, with modification by the mineral composition of the aquifer matrix. Where discharge from shallow bedrock aquifers is a primary source of alluvial-aquifer recharge, surface water quality is similarly influenced.

Major aquifer (sandstone)—Consolidated bedrock formations composed primarily of permeable coarser-grained lithologies, such as sandstone and conglomerate, commonly supply useable quantities of groundwater. In some cases, sandstone aquifers yield large quantities of good quality groundwater. Most of the groundwater stored in these aquifers is held in the sandstones' primary porosity. Porous flow is generally dominant; however, fracture flow can be significant in structurally deformed areas. Within the interior valleys, the sandstone aquifers are mostly horizontal, and some are widespread. Sandstone sequences that compose the Tertiary Wasatch/Fort Union aquifer system are the most productive sandstone aquifers in the NERB. Mesozoic sandstone aquifers are exposed by erosion along the ridges and flanks of the NERB highlands (pls. 1 and 2) and may contain accessible groundwater resources for several miles downdip of outcrop areas. Groundwater quality tends to decrease with increasing depth. Some sandstone aquifers may exhibit poor yields due to local heterogeneity, high content of fine-grained material, cementation, and lack of fractures. Wells must penetrate several individual water-bearing strata to provide adequate flow where sandstone layers are heterogeneous and discontinuous instead of thick and laterally extensive.

Major aquifer (limestone)—Carbonate formations are composed primarily of Paleozoic and lower Mesozoic limestones or dolomites that occur throughout Wyoming and are present in all seven major river basins. Well production rates are highly variable in limestone aquifers. Localized areas of vigorous groundwater flow and high productivity are present where enhanced secondary permeability has developed along solution-enlarged fractures caused by structural deformation and groundwater circulation. In the NERB, these aquifers are exposed primarily along the ridges and flanks (pl. 2) of the Bighorn Mountains, Black Hills, and Hartville Uplift, where thrust fault hanging walls have been eroded away to expose carbonate formations. In Wyoming, examples of major carbonate aquifers include the Madison, Wells, Darby, and Bighorn formations. Depending on the degree of enhanced permeability, the major limestone aquifers can contain accessible groundwater resources for several miles down dip of their outcrop areas. However, they generally are more deeply buried than the overlying sandstone aquifers, and accessibility becomes progressively difficult as burial depths increase.

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

Marginal aquifer—These consolidated bedrock formations host mostly low-yielding wells (1–5 gpm) that may be suitable for domestic or stock use. Sandstone beds are the primary source of groundwater in marginal aquifers, although fractured fine-grained strata and coal seams yield water locally. Marginal aquifers rarely yield substantial quantities of groundwater, and then only under favorable local conditions. The permeability of marginal aquifers is generally low enough that in some areas they also function as minor (leaky) confining units.

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

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

The Wyoming Statewide Framework Water Plan (WWC Engineering and others, 2007; fig. 4-9) classified the NERB geologic units; the more common names used in the framework water plan for time equivalent stratigraphic units are noted in parentheses:

Major Aquifer—Alluvial

Quaternary alluvium

Major Aquifer—Sandstone

- Arikaree Formation
- Wasatch, Fort Union, Lance, and Fox Hills formations
- Inyan Kara Group

Major Aquifer—Limestone

- Tensleep and Minnelusa formations
- Madison Group and Bighorn Dolomite

Minor Aquifer

- Quaternary non-alluvial deposits
- Mesaverde and Frontier formations
- Phosphoria and Spearfish formations
- Minnekahta Limestone
- Deadwood Formation

Marginal Aquifer

- White River and Sundance formations
- Major Aquitard (Confining Unit)
- Lewis, Cody, Skull Creek, and Pierre shales
- Niobrara, Goose Egg, and Spearfish formations
- Precambrian rocks

While WWC Engineering and others (2007) provide a general summary of the groundwater resources of the seven major drainage basins of Wyoming, the updated individual river basin plans provide a greater level of hydrogeologic detail and analysis. Plate 2 summarizes the hydrogeology developed by the USGS and WSGS for this study. Detailed descriptions of the hydrostratigraphic units are contained in chapter 7. Correlations between WWC Engineering and others (2007) and the hydrogeology presented in this study are explained on plates 4 through 6.

5.4 GROUNDWATER CIRCULATION IN THE NERB

The geologic setting of the NERB was introduced in chapter 3 and discussed in detail in chapter 4. Like other large Wyoming river basins, Laramide uplifts and associated structural basins dominate geologic structure in the NERB (chap. 4, pl. 1, and figs. 4-2 through 4-11). Major Laramide uplifts in the NERB include the Bighorn Mountains, the Casper Arch, the Hartville Uplift, and the Black Hills. The Powder River structural basin covers much of the NERB, and the headwaters of the South Fork of the Powder River are located in a small portion of the northeastern Wind River structural basin. The following sections discuss the general characteristics of groundwater circulation in Quaternary and Tertiary basin deposit and Laramide structural aquifers. These groundwater systems, however, are not hydrologically isolated from each other. Surface water and groundwater circulate freely from Laramide uplifts to the basin deposits and between the Quaternary and Tertiary basin aquifer systems.

Groundwater circulation in the bedrock aquifers of the NERB is largely controlled by fault and fracture zones that act as hydraulic barriers or conduits for groundwater. The effects that faults or fractures exert on groundwater flow can be complex. Numerous physical characteristics of the fault or fracture set, such as its type (shear or extention), spatial extent, deformation history, aperture (size of its openings), fluid chemistry and reactions, and orientation, can affect the direction and magnitude of groundwater flows. Other factors that can influence groundwater circulation include the geospatial, hydraulic, and lithologic properties of faulted rock units and the fault's hydraulic connectivity and spatial relationship to other faults and fracture sets.

Faults most commonly act as barriers that impede the flow of groundwater across strike in two ways. First, relatively impermeable rocks can be juxtaposed with more permeable units in the adjacent fault wall by the displacement of stratigraphic units. Second, friction between fault walls during displacement can grind rocks into fault gouge (clay-like, fine-grained, low-permeability sediments) that fills void space between fault surfaces and impedes the flow of groundwater. In either case, the flow of groundwater can be redirected either horizontally, along the strike of the fault, or vertically, depending on the hydraulic pressure gradients of the surrounding aquifers and confining layers. Many of the springs in the NERB, particularly along the eastern flank of the Bighorn Mountains, occur in proximity to faults where horizontal groundwater flow has been disrupted and redirected upward to the surface under artesian conditions (fig. 5-1 and pl. 3).

In contrast, groundwater flows in rocks adjacent to the fault plane can be enhanced by secondary faults, fractures, and folds that form in damage zones, which may extend for hundreds of feet on either side of a main fault. If the damage zones are hydraulically connected to a network of other faults, they can convey water to springs and wells from areas that cover several square miles. The hydrogeologic heterogeneity created by faults can make it difficult to accurately determine the dominant patterns of groundwater circulation in heavily faulted regions, even in areas where numerous monitoring wells exist.

5.4.1 Groundwater circulation in Quaternary aquifers (Thamke, 2014; Long and others, 2014)

Unlike other major river basins in Wyoming, Quaternary alluvial aquifers play a relatively minor role in the NERB (figs. 8-1 through fig. 8-5). Nearly all of the basin's irrigation wells (fig. 8-1), and most of the wells permitted for livestock (fig. 8-2), municipal (fig. 8-3), and domestic (fig. 8-4) uses, are located outside the alluvial aquifer system. This is due to the readily available fair to good quality groundwater in Tertiary and early Cretaceous aquifer systems exposed throughout much of the area (Thamke and others, 2014). In contrast, alluvial groundwater quality, particularly along the Powder River, is relatively poor, and primarily suitable only for livestock use (Ringen and Daddow, 1990). Long and others (2014) report that the alluvial aquifer system is recharged primarily by direct infiltration of precipitation, discharge from Tertiary bedrock aquifers, and infiltration of streamflows in losing reaches of headwater streams. Evapotranspiration and groundwater discharges into surface water flows constitute the principal forms of aquifer discharge. Groundwater in the NERB generally flows through Tertiary basinal units parallel or toward Quaternary stream channels to discharge, in part, as baseflow (Thamke and others, 2014).

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

Huntoon (1993, and references cited therein) developed a conceptual model of groundwater circulation in the Bighorn and Platte River Laramide structural basins.

The central thesis of this model states the groundwater recharge and circulation in the major uplifts that surround the structural basins are controlled by anisotropic permeability, developed in large-displacement thrust faults, reverse-fault-cored anticlines, and associated fractures during Laramide compressional deformation and altered during subsequent extensional periods. The main components of this conceptual model include:

- Wyoming foreland mountain ranges consist of large-scale uplifts situated atop large-displacement (thousands of feet) basement thrust faults with fault-severed strata on one side and homoclinal dipping strata on the other.
- The compressional processes that shaped the basins during the Laramide orogeny also produced smaller structures such as reverse and thrust-cored asymmetric anticlines within the basins.
- Groundwater circulation is not only controlled by Laramide structures, but also alters the hydrogeology of Laramide structures:
    - º Fracture (secondary) permeability within carbonate strata associated with faulting and folding has been enhanced by carbonate dissolution.
    - º Any fracture can potentially enhance permeability, even if formed in a compressional environment (e.g., the trough of a synclinal fold).
    - º Fractures parallel or oblique to the crests of folds, along with bedding-plane partings, formed during anticlinal folding. These fractures are extensional and have maximum potential for developing dissolution-enhanced, highly anisotropic permeability. Where extensional fractures develop, their permeability dominates local groundwater circulation. Groundwater circulation within areas of highly anisotropic fracture permeability along the crests of anticlinal folds is inhibited across the structural trend and tends to converge within the fractures developed parallel or oblique to the folds.
    - º Large-displacement thrust faults and smaller reverse and normal faults can sever an aquifer's hydraulic connection between recharge areas and the deeper basin interior. Separate groundwater circulation systems develop in both the hanging wall and footwall of major uplift-bounding, large-displacement faults.
    - º Within synclinal folds the rocks are highly compressed, and interstitial and fracture porosity is decreased.
    - º Faults can act as either conduits or barriers to flow depending on structural regime, diagenetic/cementation history, connectivity between hydrogeologic units, relationship to other, proximal faults, and relationship to inherited—ancestral—structures they overprint, etc.
- Karst developed along pre-existing fractures within the major carbonate aquifers during erosion and exposure of the recharge areas, and ongoing karstification, have greatly enhanced the permeability of these aquifers around the perimeters of Wyoming's Laramide basins.
- To a lesser extent, paleokarst, developed when the carbonate strata were exposed during Late Mississippian time, has enhanced permeability; however, the paleokarst has largely been filled in with sediments that reduce permeability.
- Intercrystalline permeability in major carbonate aquifers is generally very low.
- Groundwater circulation primarily parallels bedding. Vertical circulation within the deep artesian basins is very limited except along faulted and fractured anticlines where the permeability of confining units is enhanced.
- Brittle strata (sandstone, limestone, and dolomite) are more prone to fracture during deformation than fine-grained strata (shale, claystone, and mudstone). Fine-grained strata are also more ductile, and small fractures within these units tend to close and seal under compaction.
- Artesian pressure within the basins increases with depth as the recharge areas of deeper, carbonate aquifers are exposed at generally higher elevations in surrounding mountain ranges.
- Large production from major carbonate aquifers requires areas of large solution-enhanced permeability (modern karstification), which are developed within and down gradient of recharge areas along homoclinal (not fault-severed) flanks of the Laramide uplifts where these aquifers are exposed. The distance that conditions favorable for large yields of acceptable-quality water extend into the basins depends on the trend and continuity of the controlling structure. Large anticlines trending normal or slightly oblique to the perimeter of the

basin will generally provide the greatest recharge to the deeper basin and the best opportunities for high-yield wells.

- Although homoclinal margins exhibit hydraulic and stratigraphic continuity, areas that lack subsidiary structures and associated fracturing of the carbonate aquifers have had less opportunity to develop solution-enhanced permeability, and therefore accept less recharge. With less groundwater circulation, dissolution-enhanced permeability in recharge areas does not continue into the basins due to diagenetic processes such as compaction, cementation, and recrystallization that destroy porosity and permeability. Therefore, transmissivity decreases progressively basinward, and recharge is rejected at springs at the base of the mountains, generally near the location where a significant confining unit covers carbonate aquifers. The difference in diagenetic conditions between recharge areas and the basins increases over time proportional to groundwater circulation (more circulation causes increased dissolution). Nevertheless, homoclinal areas where carbonate aquifers exhibit significant karstification may be favorable groundwater development prospects.

- Groundwater in the major carbonate aquifers at homoclinal basin margins is generally of good quality, and high yields can be obtained under the right conditions.

- In areas where recharge is rejected, surface and groundwater are interconnected.

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

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

- Synclines and the footwall sides of fault-severed aquifers are not good prospects for groundwater development.

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

The conceptual model, described above, provides reasonable explanations for the presence or lack of available groundwater resources for municipal water supplies in the NERB. Communities such as Sheridan, Buffalo, Story, and Kaycee, which are located below the fault severed eastern flank of the Bighorn Mountains, must either depend on surface water to meet municipal requirements or obtain groundwater from Paleozoic wells sited upgradient of the fault. In contrast, numerous municipal wells are sited along the homoclinal western flank of the Black Hills (fig. 8-3).

The conceptual model also presents obvious implications for groundwater exploration and development, and these concepts have facilitated the successful completion of groundwater development projects throughout the state. Clearly, identifying and mapping structures in targeted groundwater prospects is an important aspect of any groundwater exploration project including those within the NERB.

Groundwater circulation in the major aquifer systems of the NERB is discussed further in chapter 7. Several of the components of the conceptual model described above are illustrated in figure 5-1.

5.4.3 Groundwater circulation in Tertiary basin fill aquifers (Thamke, 2014)

The most widely used source of groundwater in the NERB is the Tertiary Fort Union/Wasatch aquifer system (Thamke, 2014; SEO, 2016). Long (2014) noted groundwater circulation in the Tertiary system originates as recharge from direct precipitation and losing reaches of streambeds. Groundwater in the Tertiary system generally flows northward, except in the southern Powder River structural basin where it flows eastward (Thamke and others, 2014). Groundwater in Tertiary hydrostratigraphic units is lost to evapotranspiration, discharges to surface drainages (Thamke and others, 2014), or exits Wyoming as groundwater outflows in the Powder River Structural Basin or the Upper Niobrara and Cheyenne river basins. The northern flow of groundwater and its discharge to streams is shown in the interactive potentiometric surface map contained in figure 1-2 of Thamke and others (2014; https://pubs.usgs.gov/sir/2014/5047/appendix/appendix_figures/figure1_2_sir2014-5047.pdf). Additional discussions of groundwater circulation can be found in chapter 7.

5.5 NATURAL GROUNDWATER QUALITY AND HYDROGEOCHEMISTRY

The practical availability of a groundwater resource depends on a combination of hydrologic, technical, legal, institutional, and cultural factors. The feasibility of development and potential uses for a groundwater resource primarily depend on water quality. For this study, the USGS compiled groundwater quality data for the NERB hydrogeologic units (sec. 5.6) from several sources. These data confirm that the best quality groundwater is generally found in regions closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulating through or residing in the aquifer.

Factors that affect groundwater quality include the type and density of vegetation in recharge areas, mineral composition, grain size, transmissivity, rate of circulation, and temperature of the vadose zone and aquifer matrix. This generalization is more applicable to the minor and marginal aquifers of the NERB than to the major aquifers, within which groundwater circulation is relatively (often substantially) more vigorous. Groundwater quality in the NERB varies from fresh water, with total dissolved solids (TDS) less than 1000 mg/L (ppm) that is suitable for any domestic purpose, to briny, deep, oil field aquifers unsuitable for virtually any use, with TDS greater than 300,000 mg/L.

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

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

Section 5.5.1.3 contain descriptions of the methods used to access, screen, and statistically summarize water quality data for this report. Detailed discussion of water quality analyses of samples collected from the NERB aquifers and their component geologic and lithostratigraphic units is provided in chapter 7.

5.5.1 Groundwater quality

This section describes how data on chemical constituents in groundwater for the NERB study area were accessed, compiled, screened, and statistically summarized.

5.5.1.1 Regulation and Classification of Groundwater

Groundwater quality in Wyoming is regulated by two agencies. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division (WQD) regulates groundwater quality in Wyoming and the U.S. Environmental Protection Agency (USEPA) Region 8 Office, headquartered in Denver, regulates the public water systems located within the state. Each agency has established groundwater standards, and revises and updates them periodically.

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

Wyoming Groundwaters (http://deq.wyoming.gov/wqd/resources/rules-regs/), as:

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

5.5.1.2 Standards of groundwater quality

In this report, groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, based on EPA and WDEQ standards (table 5-1) and summary statistics for environmental and produced water samples tabulated by hydrogeologic unit as quantile values (apps. E–H). In assessing suitability for domestic use (Wyoming Class I groundwater), USEPA health-based standards of Maximum Contaminant Levels (MCLs) and Lifetime Health Advisory Levels (HALs) are used as guides (however, these standards are not legally enforceable for any of the sampling sites used in this study). USEPA Secondary Maximum Contaminant Levels (SMCLs), which generally are aesthetic standards for domestic use, WDEQ Class II groundwater standards for agriculture, WDEQ Class III standards for livestock, and WDEQ Class IV standards for industry also are used as guides for assessing suitability.

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

Water-quality concentrations are compared to three types of USEPA standards: MCLs, SMCLs, and lifetime HALs. The USEPA MCLs (U.S. Environmental Protection Agency, 2012) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections or regularly serve at least 25 individuals. The purpose of MCLs is to protect public health by limiting the levels of contaminants in drinking water. MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. The MCLs are, however, a valuable reference when assessing the suitability of water for these uses.

USEPA SMCLs (U.S. Environmental Protection Agency, 2012) are non-enforceable guidelines regulating contaminants in drinking water that may cause cosmetic effects (such as skin or tooth discoloration) or have negative aesthetic effects (such as taste, odor, or color) in drinking water. Lifetime HALs are based on concentrations of chemicals in drinking water that are expected to cause any adverse or carcinogenic effect over a lifetime of exposure (U.S. Environmental Protection Agency, 2012). 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.

Water-quality standards for Wyoming classes II, III, and IV groundwater (Wyoming Department of Environmental Quality, 2005) 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

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

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

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

[1] Selected from U.S. Environmental Protection Agency 2012 Edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2012).

[2] Selected from Wyoming Department of Environmental Quality Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters (Wyoming Department of Environmental Quality, 2005, table 1, p. 9).

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

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

[5] The 300 picocuries per liter standard is a proposed Maximum Contaminant Level, whereas the 4,000 picocuries per liter standard is a proposed alternative Maximum Contaminant Level for communities with indoor air multimedia mitigation programs (U.S. Environmental Protection Agency, 1999).

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 TDS standard established as part of underground injection control regulations (U.S. Environmental Protection Agency, 2017). 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 uses.

5.5.1.3 Sources, screening, and selection of data

Groundwater-quality data compiled through 2015 were gathered from several electronic databases, including the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/wy/nwis/qw/; U.S. Geological Survey, 2015a), the USGS Produced Waters Database (PWD) (http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx; U.S. Geological Survey, 2015b; Blondes and others, 2017), and a large data retrieval from the Wyoming Oil and Gas Conservation Commission (WOGCC) database [data retrieval provided by WOGCC staff (Karl Taboga, Wyoming State Geological Survey, written commun., 2015); database available at http://wogcc.state.wy.us/legacywogcce.cfm]. In addition, groundwater-quality data were obtained from the following reports: Crawford (1940); Littleton (1950); Bradley (1956); Kohout (1957); Whitcomb (1960, 1963, 1965); Whitcomb and Gordon (1964); Whitcomb and Morris (1964); Lowry and Cummings (1966); Whitcomb and others (1966); Crist and Lowry (1972); Wells and others (1979); Collentine and others (1981); Feathers and others (1981); Richter (1981); Plains Engineering (1982); Busby and others (1983); Larson and Daddow (1984); Western Water Consultants, Inc. (1984, 1996, 1997); Howard, Needles, Tammen, and Bergendoff (1985, 1987); Trihydro Corporation (1985, 1996, 2013, 2015); Anderson and Kelly, Inc. (1986); Bearlodge Ltd, Inc. (1986, 1991, 1994); Lowry and others (1986); Weston Engineering, Inc. (1991a,b, 1992, 1994, 2002, 2003, 2006); HKM Associates (1992a,b); James M. Montgomery, Consulting Engineers, Inc. (1992); Wester-Wetstein and Associates (1993, 1999, 2000, 2003a,b, 2004a, 2006); Soda Butte Services, Inc. (1994, 1995); Wyoming State Engineer's Office (1995); Banner Associates, Inc. (1996, 2002); Grizzly Engineering, Inc. (1999); Rice and others (2000); Frost and others (2002); Pearson (2002); EnTech, Inc. (2003, 2004, 2013b); Stetson Engineering, Inc. (2005, 2009); Campbell (2007); Campbell and others (2008); McLaughlin Water Engineers, Ltd. (2008); Olsson Associates (2008); Camp Creek Engineering, Inc. (2010); WWC Engineering and Wyoming Groundwater (2011); HDR Engineering, Inc. (2012, 2015); Quillinan and Frost (2012); WLC Engineering, Surveying and Planning (2012); Baker and Associates, Inc. (2014); Wyoming Groundwater, LLC (2014); and DOWL (2015).

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 TDS 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 chapter 7 (figs. 7-4, 7-5, and 7-6).

Many of the groundwater sites in the NERB study area were sampled more than once; however, only one groundwater sample from a given site was selected for this study to avoid biasing the statistical results in favor of multiple-sample sites. In choosing among multiple samples from a site or well/hydrogeologic unit combination, either the most recent sample, the sample with the best ion balance (closest to 0), or the sample with the most complete analysis was retained in the final dataset.

Chemical analyses of groundwater-quality samples available from the USGS PWD were included in the dataset used for this report. Only those PWD samples from a wellhead or from a drill-stem test were included in the dataset. Samples not 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 were 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.

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

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 environmental groundwater-quality samples from some aquifers 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 aquifers, it probably allows for a more accurate characterization of the units in areas where they are shallow enough to be used economically.

5.5.1.4 *Groundwater quality characteristics*

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the NERB study area, even in water from shallow wells. This is not surprising, given the arid climate and small rate of recharge in much of the study area. High TDS can adversely affect the taste and odor of drinking water, and a high TDS concentration in irrigation water has a negative effect on crop production. High TDS concentrations also cause scale build-up in pipes and boilers. The USEPA has not set an MCL for TDS; however, the USEPA SMCL for TDS is 500 milligrams per liter (mg/L; U.S. Environmental Protection Agency, 2012). The TDS concentration is loosely termed salinity. Groundwater samples are classified in this report in accordance with the USGS salinity classification (Heath, 1983), as follows (table 5-2):

Table 5-2. USGS water salinity classification.

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

The sodium-adsorption ratio (SAR) represents the ratio of sodium ion activity (concentration) to calcium and magnesium ion activities; it is used to predict the degree to which irrigation water enters into cation-exchange reactions in the soil. High SAR values indicate sodium is replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR is used in conjunction with information about soil characteristics and irrigation practices in the area being examined. The high SAR of waters in some hydrogeologic units in the NERB study area indicates that these waters may unsuitable for irrigation.

Many groundwater-quality samples included in the dataset for this report contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA standards (U.S. Environmental Protection Agency, 2012) and WDEQ groundwater-quality standards (https://rules.wyo.gov/Search.aspx?mode=1). Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2012). High chloride concentrations can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops (U.S. Environmental Protection Agency, 2012; Bohn and others., 1985, and references therein). Low concentrations of fluoride in the diet have been shown to promote dental health, but higher doses can cause health problems such as dental fluorosis—a discoloring and pitting of the teeth—and bone disease (U.S. Environmental Protection Agency, 2012). Both iron and manganese may adversely affect the taste and odor of drinking water and cause staining (U.S. Environmental Protection Agency, 2012). High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.5.1.5 *Statistical analysis*

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

This section describes the approaches used to assemble, analyze, and present water-quality data for samples of groundwater from the NERB study area. From these data, summary statistics were derived for physical properties and major-ion chemistry of groundwater in hydrogeologic units in the NERB study area, as tabulated in appendices E–H for environmental water samples. Environmental water is natural groundwater as produced from wellheads and springs; it is not associated with hydrocarbons. Produced water is water co-produced (pumped out of the ground) with oil and gas or water samples collected during oil and gas exploration and production. The water-quality data for the hydrogeologic units in the NERB study area also are compared to USEPA and WDEQ standards for various water uses, as the groundwater-quality standard exceedance frequencies presented in this report.

Standard summary statistics (Helsel and Hirsch, 1992) for uncensored data were used for physical characteristics and major-ion chemistry of environmental water samples (apps. E–H). Censored data are data reported as above or below some threshold, such as "below detection limit" or "less than 1 mg/L." For a very small number of major-ion samples, censored values ("less than") were reported for a major ion constituent. These censored values were treated as uncensored values at the laboratory reporting level for statistical analysis. For uncensored datasets with a sample size of 1, only a maximum value is reported in appendices E–H; for a sample size of 2, minimum and maximum values are reported; for a sample size of 3, minimum, median (50th percentile), and maximum values are reported; for sample sizes of 4 or more, minimum, 25th percentile, median (50th percentile), 75th percentile, and maximum values are reported.

Concentrations of nutrient, trace element, and radiochemical constituents were reported as uncensored values in environmental water datasets for some hydrogeologic units. For nutrient, trace element, and radiochemical datasets without censored values, the convention used for uncensored data was used to report summary statistics. Environmental water datasets for other hydrogeologic units contained censored values, including censored values that had multiple detection limits. Rather than assign the laboratory reporting level or another arbitrary value to the censored results, the Adjusted Maximum Likelihood Estimation (AMLE) technique was used for statistical analysis of nutrients, trace elements, and radiochemical constituents in this report. The AMLE technique is for left-censored data and computes summary statistics for results with multiple detection limits (Helsel and Cohn, 1988). Left-censored data consists of values that are less than the analytical limit of detection, and the censored values range from 0 to the limit of detection. The technique requires that at least three values are uncensored for a sample size of three or greater and that the proportion of censored values does not exceed 90 percent in order to compute percentiles. The AMLE technique computes statistics for the interquartile range and determines the maximum uncensored value for the dataset; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. A minimum value also is reported when the minimum value was an uncensored value that was less than the 25th percentile that was calculated by the AMLE technique. In some cases, environmental water datasets for a constituent and hydrogeologic unit could not meet the minimum sample size or uncensored value requirements for the AMLE technique. For those cases, either a censored minimum and uncensored maximum are reported or a censored maximum value is reported. For constituents within a hydrogeologic unit that had a sample size of 1, a minimum value (censored or uncensored) is reported; for a sample size of 2, a minimum value (censored or uncensored) and maximum uncensored value are reported or only a maximum censored value is reported; for a sample size of 3, a minimum value (censored or uncensored), a median uncensored value and maximum uncensored value are reported or only a maximum censored value is reported. In some cases, a dataset for a constituent and hydrogeologic unit was insufficient for determining complete summary statistics with the AMLE technique; however, individual samples could be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedance frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedance frequencies were calculated and reported as counts for a hydrogeologic unit. When only one sample was available and a water-quality constituent exceeded a regulatory standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent.' Groundwater-quality standard exceedance frequencies were determined using the filtered analyses for a constituent because filtered analyses were more common (or frequently were the only analyses available). Only samples for a constituent that were analyzed at a laboratory reporting level that was equal to or less than the specific groundwater-quality standard for that constituent were included in the exceedance analysis. For example, if five samples were analyzed for manganese and the results were <10 μg/L, <20 μg/L, 53 μg/L, 67 μg/L, and <100 μg/L, only the four samples with results of <10 μg/L, <20 μg/L, 53 μg/L, and 67 μg/L could be compared to the SMCL of 50 µg/L for manganese. The sample with the value of <100 µg/L could not be used because it cannot be determined if its value was less than 50 µg/L or greater than 50 µg/L. For this example, the groundwater quality exceedance text would indicate that 50 percent of samples exceeded the SMCL of 50 µg/L. Complete summary statistics for manganese would not be included in the appendix for the hydrogeologic unit in this example because too many of the available values were censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the dataset was not met. For this example, only a maximum value of <100 µg/L would be reported in the appendix. Descriptions of the constituents that were included in the statistical summaries for environmental water samples are summarized in the next section.

5.5.1.5.1 Environmental water samples

Environmental water samples (environmental waters) are from wells of all types except those used for resource exploration and extraction (primarily oil and gas exploration/development) 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 and other sources such as consulting engineers' reports related to water-supply exploration and development. The physical properties and constituents presented in this report are pH, specific conductance, major ions, nutrients, trace elements, and radiochemicals.

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

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

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) commonly was available and included in the dataset. If a laboratory value was not available, a TDS value was calculated by summing concentrations of individual constituents (if complete analyses were available). For this report, a filtered laboratory value of alkalinity was included in the dataset if available. If that was not available, an unfiltered laboratory value of acid-neutralizing capacity (ANC) was used for alkalinity; if that constituent was not available, a filtered field alkalinity value was used; and if that was not available, an unfiltered field value of ANC was used to report alkalinity. Some alkalinity values were computed from the bicarbonate reporting form to the calcium carbonate reporting form. These constituents are reported in milligrams per liter (mg/L).

Because there were many different types of laboratory analyses, including different analytical methods and different reporting forms (for example, nitrate 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 ammonia plus organic nitrogen (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved orthophosphate (reported as phosphorus), dissolved phosphorus (reported as phosphorus), and dissolved organic carbon. Total ammonia (reported as nitrogen), total ammonia plus organic nitrogen (reported as nitrogen), total nitrate plus nitrite (reported as nitrogen), total nitrate (reported as nitrogen), total nitrite (reported as nitrogen), total nitrogen (reported as nitrogen), and total phosphorus (reported as phosphorus), analyzed in a laboratory using unfiltered water samples, were included in the summary statistics. In addition, total organic nitrogen and total nitrogen (for both filtered and unfiltered samples), were computed using analyses of the individual constituents, and are included in the summary statistics. Nutrient constituents are reported in milligrams per liter.

Trace element constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the summary statistics for this report included dissolved aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, selenium, strontium, vanadium, and zinc. Total iron and total manganese (both unfiltered) also were included in the summary statistics. These constituents are reported in micrograms per liter (µg/L).

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

5.5.1.5.2 Produced-water samples

Produced water in the PWD is water co-produced with oil and gas extracted from petroleum (hydrocarbon) reservoirs or water obtained from drill-stem tests or exploratory wells completed in deeply buried petroleum- and non-petroleum-bearing sedimentary strata encountered during petroleum exploration. Produced-water samples are from wells, test wells, or drill-stem tests related to natural resource exploration and extraction (primarily oil and gas exploration/production). As described previously in the "Sources, screening, and selection of data" section, chemical analyses for produced-water samples were compiled from the USGS PWD and the WOGCC database. The physical properties and constituents presented in this report for produced-water samples are pH, TDS, and major ions.

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

5.5.1.6 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the NERB study area are plotted on trilinear diagrams (appendices I–L). 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 I–L). The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes a water type or hydrochemical facies (see Back, 1966).

5.6 AQUIFER SENSITIVITY AND POTENTIAL GROUNDWATER CONTAMINANT SOURCES

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the NERB.

In 1992, DEQ/WQD, in cooperation with the University of Wyoming, the Wyoming Water Resources Center (WWRC), the WSGS, the Wyoming Department of Agriculture (WDA), and the EPA, Region 8, initiated the Wyoming Ground Water Vulnerability Mapping Project to evaluate the vulnerability of the state's groundwater resources to contamination. This effort resulted in the publication of the Wyoming Groundwater Vulnerability Assessment Handbook (the Handbook) by the Spatial Data and Visualization Center (SDVC; Hamerlinck and Arneson, 1998). While the fundamental goal of the SDVC study was to develop a GIS-based tool to aid in planning, decision-making, and public education, the GIS maps and associated digital databases developed by the project have been used for numerous subsequent, related studies, such as updates to the State Water Plan. The methodology and purpose of Hamerlinck and Arneson (1998) are discussed in this section.

The aquifer sensitivity map (fig. 5-3) from the 1992 SDVC study was used to evaluate the potential for groundwater contamination in the NERB. Figures 5-4 through 5-10 show potential groundwater contaminant sources in the NERB. Data sources for figures 5-1 through 5-10 are noted on each figure and summarized in appendix C.

5.6.1 The Wyoming Groundwater Vulnerability Assessment Handbook and aquifer sensitivity

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

- Aquifer sensitivity refers to the relative potential for a contaminant to migrate to the shallowest groundwater, based solely on hydrogeologic characteristics. According to the SDVC, "Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material between ground surface and the saturated zone of an aquifer and the aquifer matrix. Aquifer sensitivity is not dependent on land use and contaminant characteristics."

- Groundwater vulnerability considers aquifer sensitivity, land use, and contaminant characteristics to determine the vulnerability of groundwater to a specific contaminant. Because pollutant characteristics vary widely, the SDVC vulnerability assessments assumed a generic pollutant with the same mobility as water.

Aquifer sensitivity and groundwater vulnerability are characteristics that cannot be directly measured but must be estimated from measurable hydrogeologic and contaminant properties, and land-use conditions. Because of the uncertainty inherent in the assessment of sensitivity and vulnerability, these parameters are not expressed quantitatively; but rather, in terms of relative potential for groundwater contamination. Because the SDVC vulnerability mapping assumed a single, generic pollutant, only the map of relative aquifer sensitivity is presented in this study. The aquifer sensitivity map (fig. 5-3) may be compared with figures 5-4 through 5-10 to identify areas of elevated risk of contamination from specific potential groundwater contaminant sources.

The SDVC study assessed aquifer sensitivity using modified DRASTIC model methodology (Aller and others, 1985) based on six independent parameters:

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

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

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

Figure 5-3 designates the relative potential for contaminants to migrate from ground surface to the uppermost groundwater (water table) to five sensitivity categories.

- The highest risk areas (46–65) are located primarily in alluvial deposits and in highly fractured mountain belts that surround the basins. The shallow depths to groundwater, high porosities of unconsolidated soils and weathered bedrock, and relatively flat topography place alluvial aquifers at higher risk of contamination. Similarly, heavily fractured bedrock, shallow groundwater within thin soil zones, and high rates of recharge characteristic of mountainous aquifers make fractured mountain units highly vulnerable to contamination.

- Medium-high ranked areas (36–45) generally extend from the edges of the highest ranked areas, across adjacent alluvial or foothill zones. Groundwater in these areas generally occurs in deeper, thinner aquifers. The soils in these zones are more mature and have higher clay and loam contents. There is less fracturing in the bedrock exposed in the foothills than in more highly deformed, mountainous areas.

- Medium ranked areas (31–35) are prevalent in the remaining dry land agricultural and grazing areas of the NERB. These areas generally have relatively thicker, well-drained, mature soils, rolling topography with minor relief (lower slopes), and greater depths to the water table.

- Medium-low ranked areas (26–30) are generally characterized by low natural precipitation, low recharge, deep water tables, rolling topography, and unfractured bedrock.

- Low ranked areas (0–25) have the deepest water tables and lower hydraulic conductivity in the vadose zone. Soils in these areas are generally poor for agriculture due to high clay content, or due to very low average precipitation, or both.

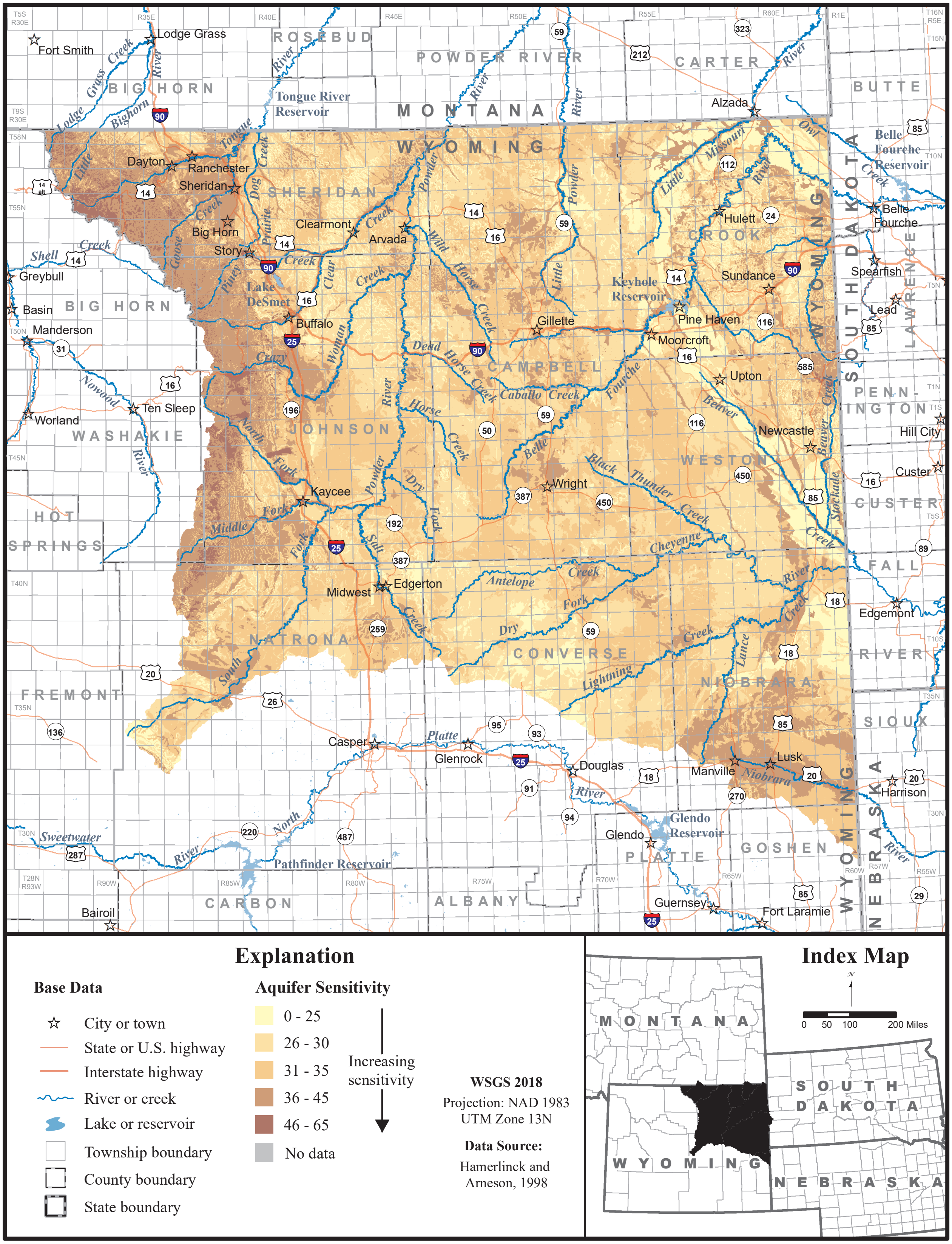


Figure 5-3. Aquifer sensitivity, NERB, Wyoming.

5.6.2 Potential sources of groundwater contamination

Figures 5-4 through 5-10 illustrate potential groundwater contaminant sources. These generally include industrial, retail, private, and public facilities that handle substantial volumes of waste and other substances with physical and chemical characteristics that, released to the environment, could migrate to the water table. Releases from these facilities would pose a potential threat primarily to unconfined aquifers and the outcrop/recharge areas of confined aquifers.

The identification of facilities that are potential sources of groundwater contamination does not imply that they are impacting groundwater resources. Generally, these facilities are strictly regulated by one or more regulatory agency to prevent contaminant releases and to protect groundwater resources, human health, and the environment.

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

WDEQ Water Quality Division:

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

WDEQ Solid and Hazardous Waste Division:

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

WDEQ Land Quality and Abandoned Mine Land Divisions:

- Class III injection wells used for mineral extraction
- Active, inactive, and abandoned mines and quarries

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, and compressor stations
- Pipelines
- Active and inactive mines and quarries

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

The infrastructure associated with the extensive oil and gas development that has taken place in the NERB is shown in figure 5-4. Additional information about petroleum infrastructure can be obtained online from: http://wogcc.wyo.gov/.

- Oil and gas fields—Petroleum development began in 1889 at the Salt Creek Oil Field and has continued to the present. Oil fields are concentrated in a broad corridor that extends from north to south in the eastern two-thirds of the NERB. Most natural gas has been produced from fields in the central Powder River and northern Tongue River drainages. In the last decade, there has been a resurgence of petroleum exploration in the southern Powder River Basin with the introduction of improved hydraulic fracturing and horizontal drilling technologies. The WSGS' Interactive Oil and Gas Map is publicly available at: http://www.wsgs.wyo.gov/energy/oil-gas-maps-publications, and provides additional detailed information about Wyoming's petroleum production.
- Pipelines—Inter- and intrastate pipelines transport a variety of liquids that if released by rupture,

malfunction, operational problems, or leaks can migrate to groundwater. Small leaks from buried pipelines can go undetected for extended periods of time, releasing substantial volumes of contaminants.

Figure 5-5 – Potential groundwater contaminant sources: classes I and V injection wells in the WDEQ UIC Program

- Classes I and V UIC injection wells—Class I underground injection wells and Class V injection facilities are regulated through the WDEQ Underground Injection Control (UIC) Program. In Wyoming, Class I wells inject non-hazardous wastes (Resource Conservation and Recovery Act (RCRA) definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal contributes a large component of injected fluids. Class I wells generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they accept for injection. In contrast, Class V facilities inject a wide range of non-hazardous fluids generally above or directly into shallow aquifers, and therefore have a substantial capacity for impacting groundwater resources. Many Class V wells in Wyoming are associated with groundwater contamination, and new injection of industrial wastes has been banned. Currently, only three Class V facilities permitted to inject industrial wastes are operational in the state of Wyoming, and these must follow stringent annual monitoring requirements. Some notable examples of Class V facilities are agricultural or storm water drainage wells, large-capacity septic systems, and various types of infiltration galleries. Class I and Class V injection facilities also generally include bulk storage tanks, pipelines, and other equipment that could release contaminants in recharge areas.

- Class III injection wells—Class III injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells inject fluids for in-situ solution mining of various minerals (e.g., uranium, sulfur, copper, trona, potash), underground coal gasification, the recovery of hydrocarbon gas and liquids from oil shale and tar sands, and experimental/pilot scale technology.

- Active and permanently abandoned Class III injector and disposal wells—Wells for disposal or for maintaining reservoir pressure in enhanced oil recovery are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources. Class II wells, which are strictly regulated by the WOGCC, the Bureau of Land Management, and the EPA, generally pose minimal potential for impacting groundwater resources by excursions from the injection interval. However, releases during surface operations or through poorly cemented well casing, though rare, are potential avenues of contamination. Class II injection wells are located within oil and gas fields.

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

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

- Commercial wastewater disposal pits—Commercial wastewater disposal pits are regulated by the WDEQ Water Quality Division (WQD) Water and Wastewater Program. These facilities deal primarily with produced water from oil and gas operations but can receive other wastes with prior approval of the WDEQ. Produced water disposed at these facilities may contain liquid hydrocarbons, which are generally recovered and sold prior to wastewater injection. Releases can occur from operational malfunctions, leaking from surface pits, and leaks from pipes and storage tanks.

- Active and expired WYPDES outfalls—Discharge of any potential pollutant from a point source into surface waters of the state requires a Wyoming Pollutant Discharge Elimination System (WYPDES) permit. During flow to surface waters, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits, and other impoundments are commonly installed along WYPDES flow paths to store water for other uses and to slow flow rates to minimize erosion and remove sediment. These installations all enhance the amount of surface flow that can infiltrate into the subsurface by increasing the time and area over which discharged water is in contact with the stream channel or storage basin. Many WYPDES outfalls shown in figure 5-6 discharge water co-produced with oil and gas development.

Figures 5-7 through 5-9 show the locations of active and abandoned mines, quarries, pits, and similar operations. These facilities and sites can impact groundwater in several ways. Stripping topsoil from an area increases infiltration rates and removes the capacity for biodegradation and retardation of contaminants within the soil horizon. Excavations can impound large quantities of water and enhance recharge or can hydraulically connect contaminants to the water table. Atmospheric exposure of metal-rich minerals can oxidize and mobilize through dissolution. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) more quickly infiltrates the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-7 – Potential groundwater contaminant sources: WDEQ/Abandoned Mine Land (AML) Program, abandoned mine sites - shows the location of abandoned mine sites inventoried and under the jurisdiction of the WDEQ AML Division. These include sites where reclamation may or may not have been completed.

Figure 5-8 – Potential groundwater contaminant sources: WDEQ LQD permitted mines, quarries and pits.

Three active mine types are regulated by the WDEQ LQD:

- Active limited mining operations (LMO) are exempt from the WDEQ's full permitting process. LMOs are restricted to a maximum of 10 acres for the life of the mine.
- Active small mines may disturb up to 10 acres per year but do not have a limit on the total area disturbed.
- Active large mines have no limit on total disturbance area or on how many acres may be disturbed per year.

Figure 5-9 – Potential groundwater contaminant sources: WSGS mapped mines, pits, mills, and plants - includes active, inactive, abandoned, and proposed facilities and sites, partially duplicating mine sites shown on figures 5-8 and 5-9. However, because the data for figure 5-9 was compiled prior to and independently of the data compiled for figures 5-7 and 5-8, it might provide a more comprehensive picture of mining locations in the NERB.

Figure 5-10 - Volunteer Remediation Program (VRP) sites, storage tanks, solid and hazardous waste facilities - permitted by WDEQ Solid and Hazardous Waste Division (SHWD) including:

- VRP sites: These are sites where soil or groundwater contamination is remediated by agreement between the SHWD and the responsible party under the Voluntary Remediation Program (VRP).
- Orphan sites: Sites where WDEQ cannot determine which party is responsible for causing or contributing to contamination, or where, under specific circumstances, additional contamination was discovered after a "No Further Action" letter was issued following previous site remediation.
- Active storage tanks: In use or temporarily out of use, above and underground storage tanks are regulated by the WDEQ/SHWD Storage Tank Program. Because releases can go undetected for long periods of time, underground storage tanks (USTs) have long been recognized for their potential to contaminate groundwater. The Storage Tank Program was developed, in large part, in response to the high number of releases from USTs.
- Commercial oil disposal pits.

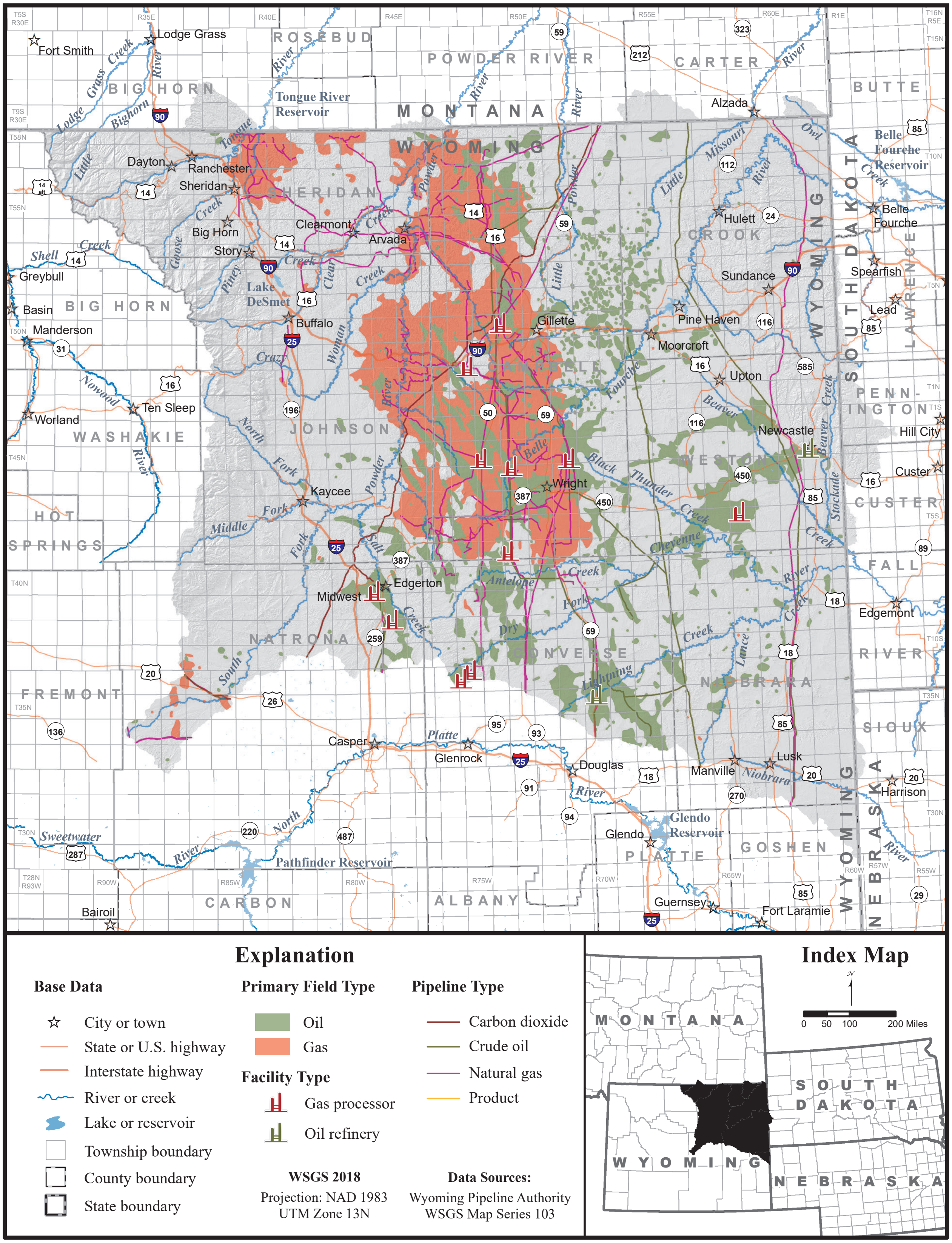


Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, gas processing plants, and Class II injection and disposal wells, NERB, Wyoming.

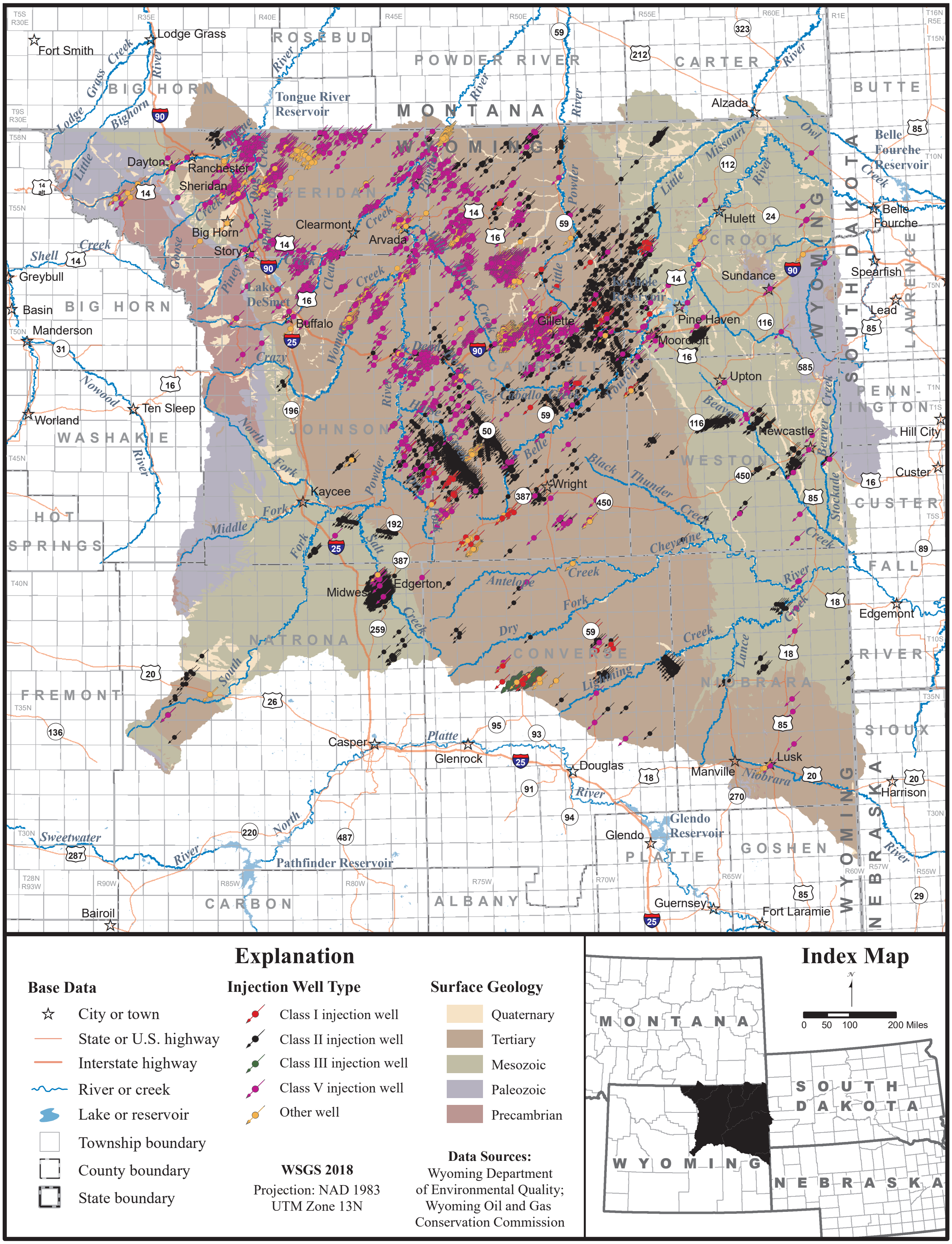


Figure 5-5. Potential groundwater contaminant sources: Class I and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, NERB, Wyoming.

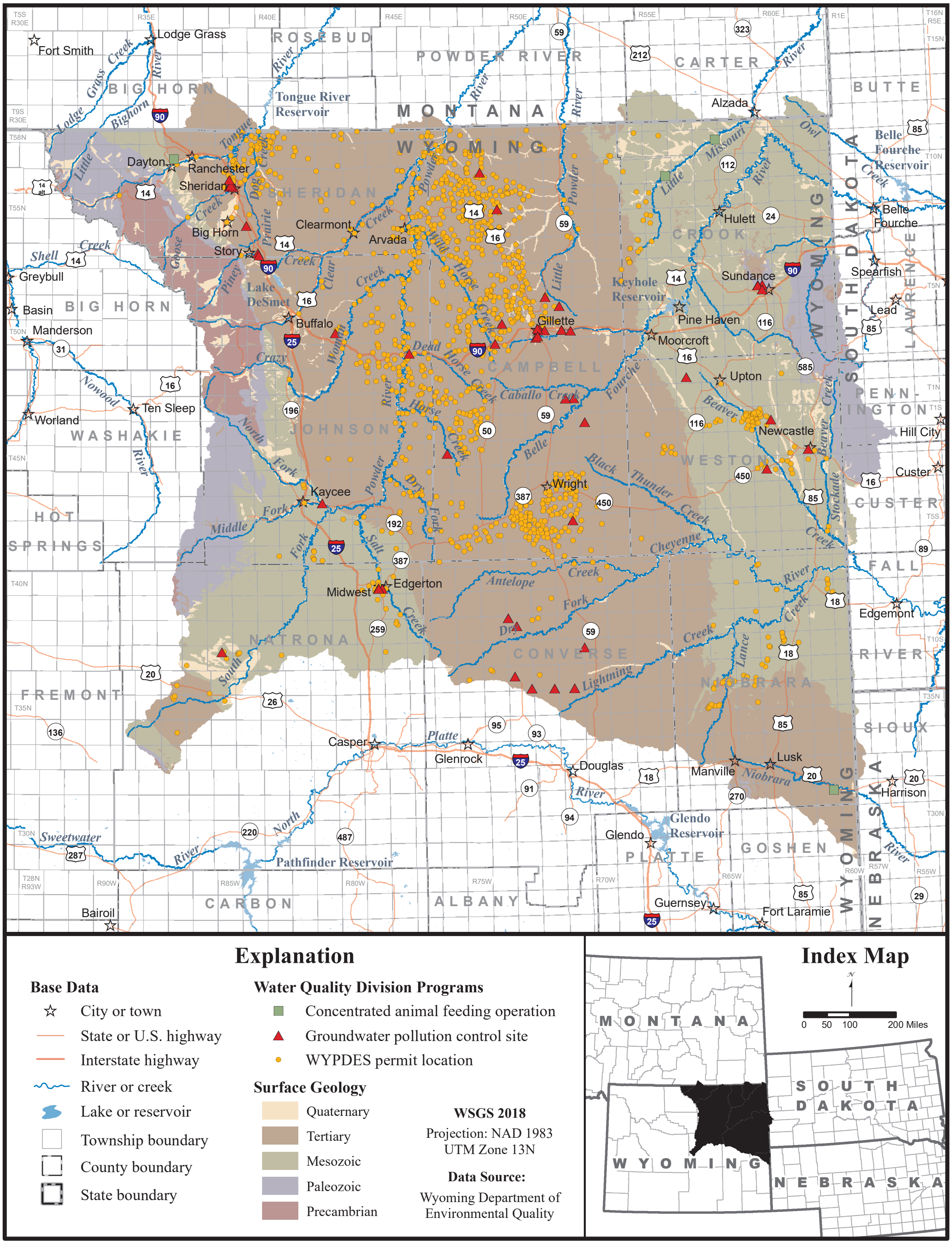


Figure 5-6. Potential groundwater contaminant sources: Active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program; WDEQ groundwater pollution control facilities and commercial disposal pits, NERB, Wyoming.

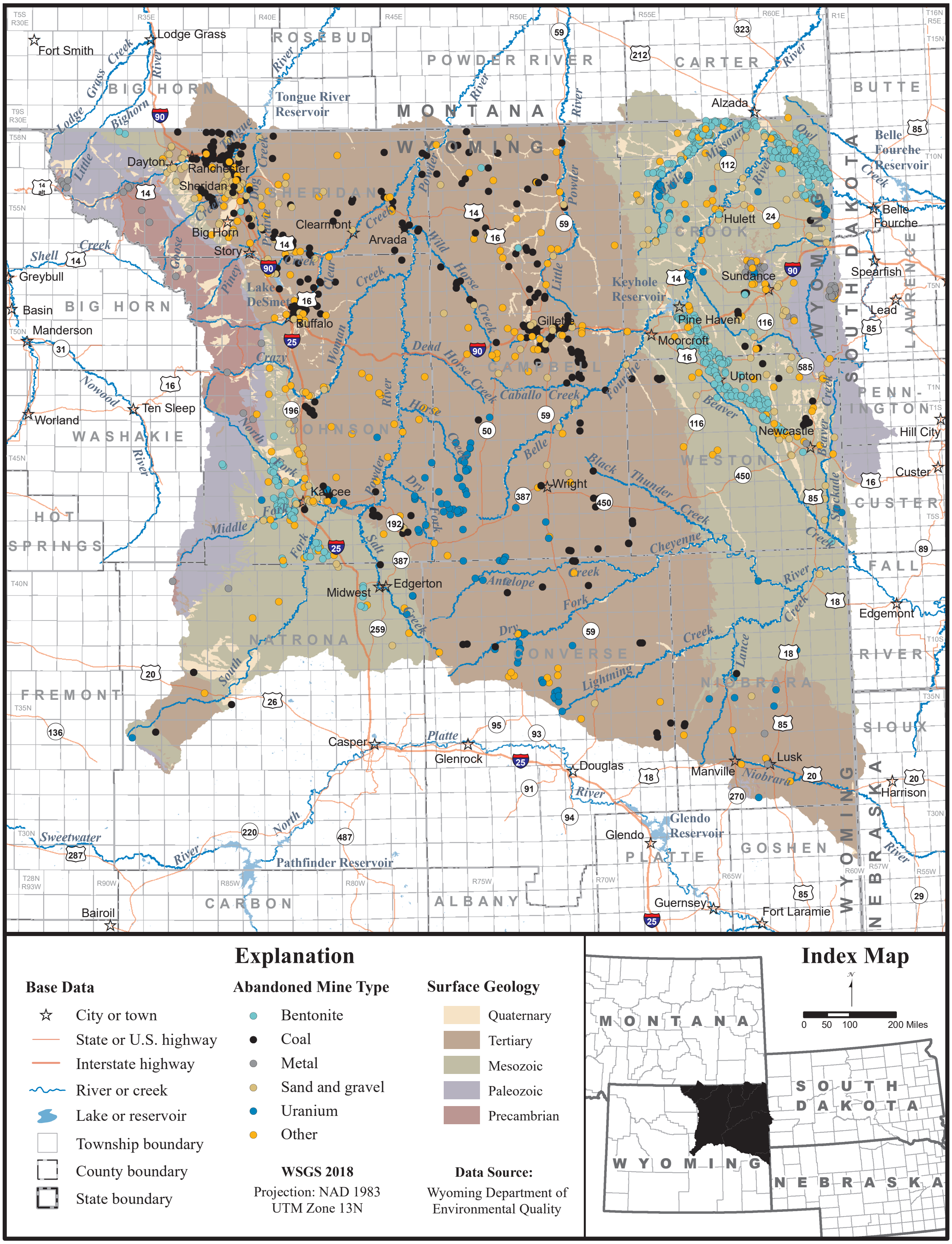


Figure 5-7. Potential groundwater contaminant sources: WDEQ Abandoned Mine Land Division abandoned mine sites, NERB, Wyoming.

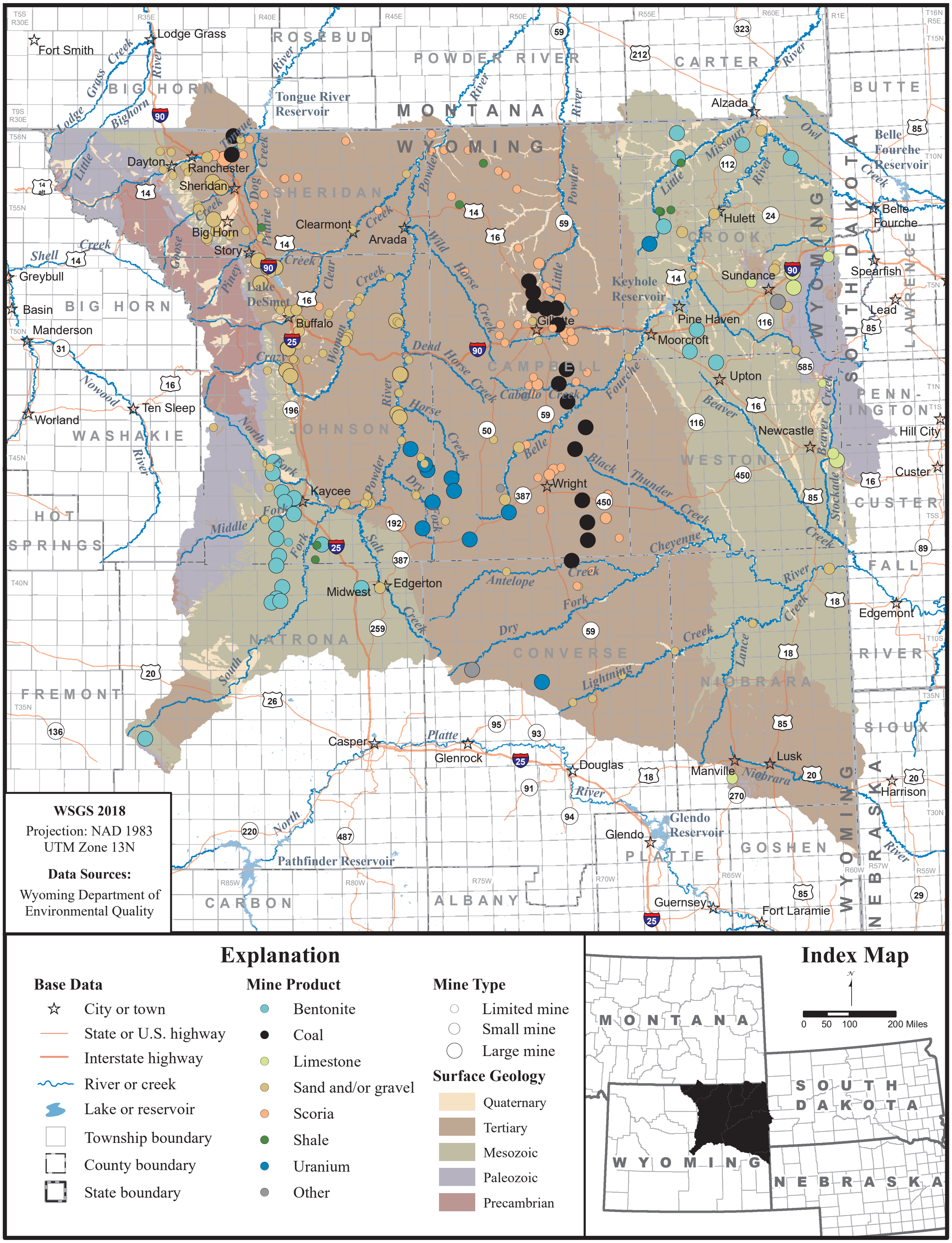


Figure 5-8. Potential groundwater contaminant sources: WDEQ Land Quality Division permitted mines, quarries, and pits, NERB, Wyoming.

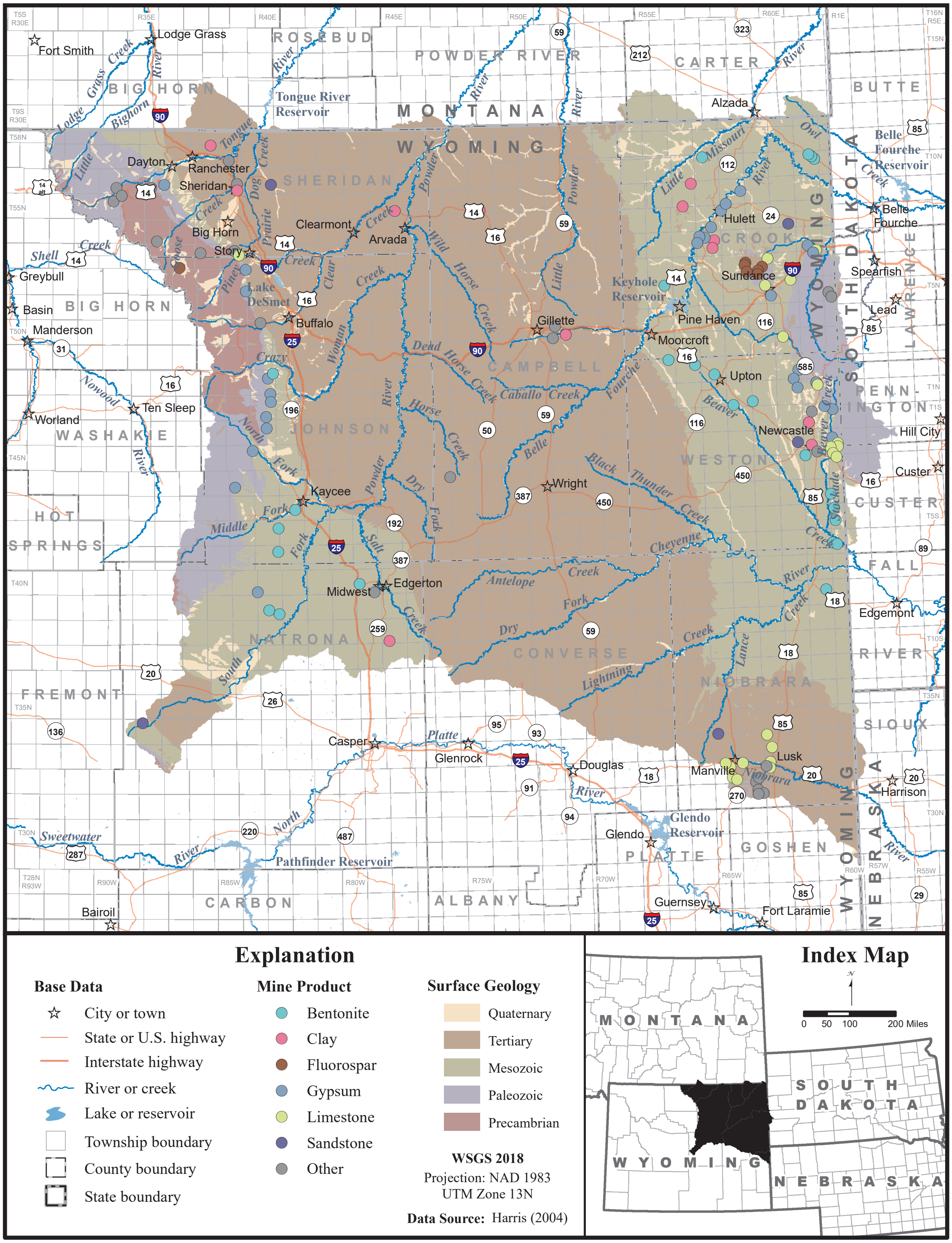


Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, NERB, Wyoming, (locations from Harris, 2004).

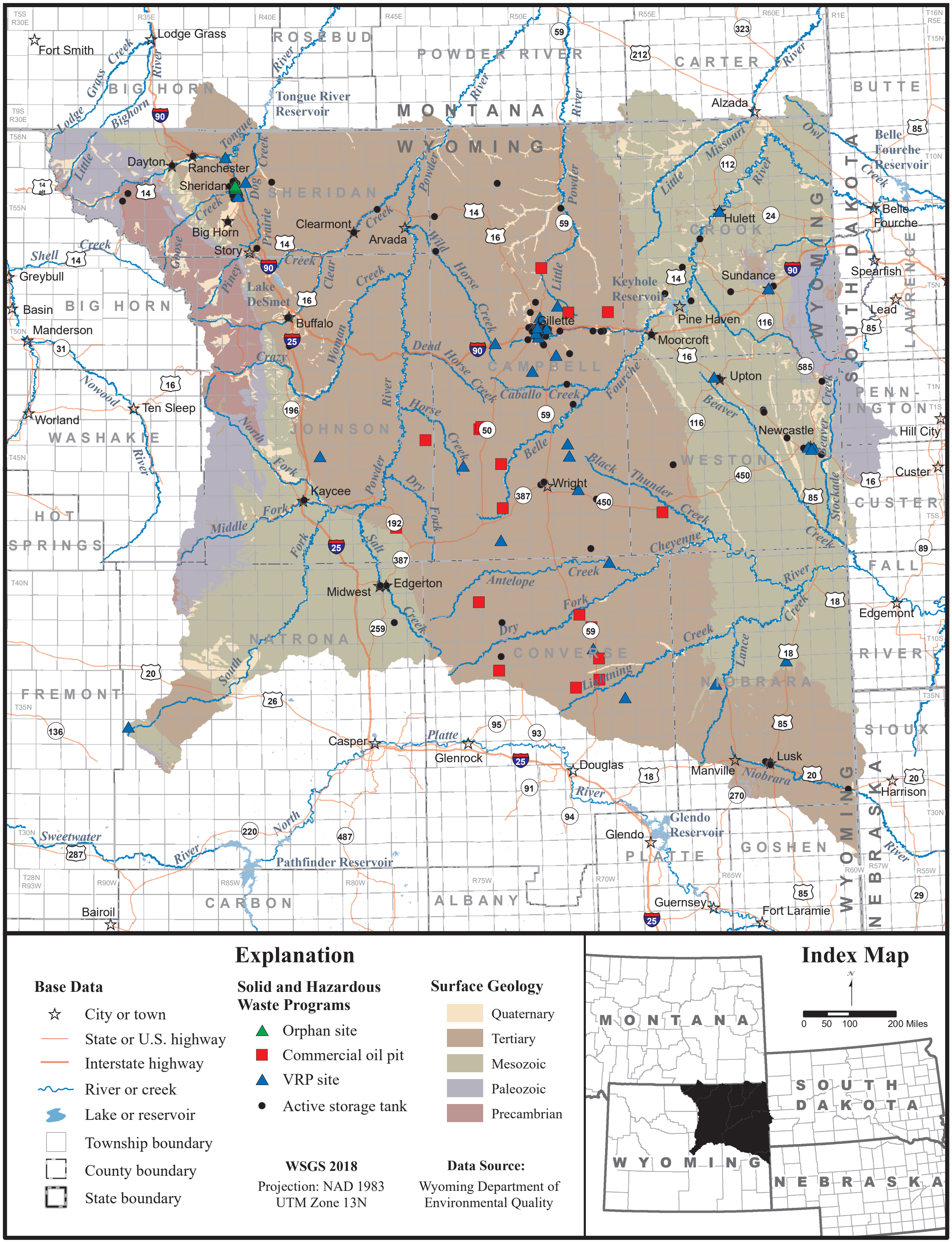


Figure 5-10. Potential groundwater contaminant sources: WDEQ permitted storage tanks, Voluntary Remediation Program (VRP), and permitted solid and hazardous waste facilities, NERB, Wyoming.

5.6.3 Discussion

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

- Although a number of public-owned treatment works (POTWs) and septic systems exist in the NERB, they were not mapped because adequate location data were not available. However, some large-capacity septic systems have been mapped as Class V injection facilities (fig. 5-5).
- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the 2002 Powder/Tongue and Northeast Basin Final Reports (HKM Engineering Inc., 2002a, b) shows the primary areas where agricultural chemicals would generally be applied in the NERB. In addition, recent USGS reports (Eddy-Miller, 2006; Eddy-Miller and Gianakos, 2002a, b; Eddy-Miller and Norris, 2001; Eddy-Miller and Remley, 2004, 2005, 2006;) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC report (Hamerlinck and Arneson, 1998) to be most vulnerable to this type of contamination. The application of pesticides and herbicides is regulated by the WDEQ Nonpoint Source Program.
- There are currently no underground coal gasification (UCG) sites in the NERB.
- SEO permitted produced water containment units, not shown in the figures, can be found on the E-Permit webpage: http://seoweb.wyo.gov/e-Permit/Common/Home.aspx.
- WOGCC water pits can be found on: http://wogcc.state.wy.us/.
- Compressor stations are not shown.
- Construction/demolition landfills, hazardous waste and used oil generators, one-time disposal authorizations, mobile treatment units, de minimus spills, and complaints were included in the data received from SHWD, but are not shown on figure 5-10 due to variable location (mobile) or relatively low potential for contaminating groundwater.

The above list and description of potential groundwater contaminant sources may be incomplete. This study may have overlooked additional potential sources associated with sufficient volumes of contaminants of concern.

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

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

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

A general discussion of these programs follows. More information can be obtained from the WDEQ WQD website, http://deq.wyoming.gov/wqd, under the Groundwater Assessment and Monitoring section.

<u>The Source Water Assessment Program (SWAP)</u>

The SWAP is a component of the federal Safe Drinking Water Act enacted to help states protect both municipal and non-community public water systems (PWSs). The program provides additional information on potential local contaminant sources. The SWAP, administered by the WDEQ Water Quality Division (WQD) and voluntary for the PWSs, includes the development of source-water assessments and protection plans, referred to as Wellhead Protection Plans (WHPs). The source-water assessment process includes: 1) determining the source-water contributing area, 2) generating an inventory of potential sources of contamination for each PWS, 3) determining the susceptibility of the PWS to identified potential contaminants, and 4) summarizing the information in a report. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming (fig. 5-11). Additional information on the SWAP in Wyoming can be accessed at: http://deq.wyoming.gov/wqd.

Water Quality Monitoring Strategy

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

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

Phases III and IV of the program are currently being conducted. A complete description of the program can be found online at: https://wy-mt.water.usgs.gov/projects/gw_monitoring/index.htm.

USGS Pesticide Monitoring Program in Wyoming

The USGS initiated a groundwater sampling program in 1995 to develop a baseline water quality dataset of pesticides in Wyoming aquifers. None of the 589 samples collected had pesticide levels exceeding the EPA Drinking Water Standards. The program is conducted in cooperation with DEQ and the Wyoming Department of Agriculture. Further program information and results are available online at: https://wy-mt.water.usgs.gov/projects/pesticide/index.htm.

WDEQ Nonpoint Source Program

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

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

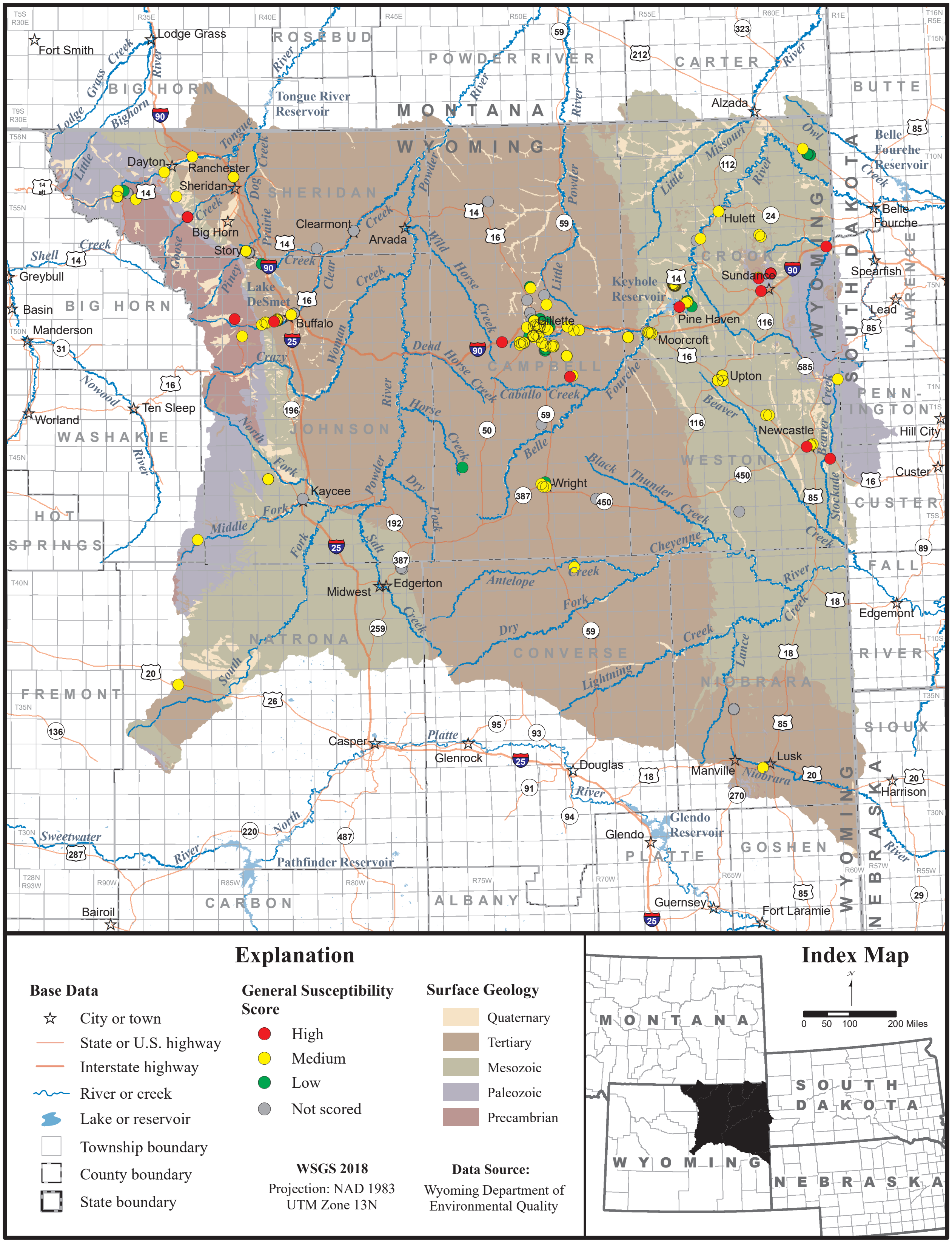


Figure 5-11. Surface Water Assessment and Protection: WDEQ Source Water and Wellhead Protection Program, NERB, Wyoming.

Chapter 6

Powder/Tongue/Northeast River Basins (NERB) hydrogeology and groundwater resources

Karl G. Taboga

Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In the NERB, the Tertiary aquifer system is the most frequently used hydrogeologic unit (Thamke and others, 2014; figs. 8-1 through 8-7). In addition, more than 15 other bedrock aquifers and their stratigraphic equivalents (fig. 7-2) provide variable amounts of useable groundwater. These aquifers range in geologic age from Paleozoic to Quaternary.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (sec. 5.1.1). In practice, the distinction between aquifers and confining units is not as clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all geologic units in the NERB, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Lebo Shale member of the Fort Union Formation is identified as an aquifer in areas where it is locally productive but is considered a confining unit elsewhere (Thamke, 2014). In addition, numerous springs discharge water from this unit at the surface (pl. 3). Permeability can vary widely within an individual geologic unit depending on its lithology and the geologic structure present. Carbonate aquifers, such as the Madison Limestone, commonly exhibit the highest yields in areas where secondary permeability (e.g., solution openings, bedding plane partings, and fractures) has developed. The great differences in permeability between and within geologic units account, in part, for the observed variation in the available quantity and quality of a basin's groundwater resources.

A primary purpose of this study is to evaluate the groundwater resource of the NERB primarily through the following tasks (chap. 1):

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

The complex geology of the NERB, as discussed in chapter 4, does not permit the basin-wide application of general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties commonly used to estimate total and producible groundwater resources. The data required for a basin-wide, aquifer-specific assessment of all groundwater resources are not available currently. Groundwater resources evaluated in this study rely on estimates (Taboga and Stafford, 2016) of the percentage of precipitation in areas where aquifer units crop out that will ultimately reach the subsurface as recharge (figs. 6-1 through 6-7) and the formulation of a basin-wide water balance (chap. 8). The technical and conceptual issues concerning recharge are discussed in section 5.1.3.

Additionally, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915). Instead, many water resource professionals now consider sustainable development of groundwater. The recharge volumes estimated in this chapter provide a first step to evaluating sustained yields for the basin's hydrologic units. The historical development of the safe yield concept and its technical context is discussed in section 5.1.4.

6.1 HYDROSTRATIGRAPHY AND RECHARGE TO AQUIFER OUTCROPS

To evaluate recharge, specific aquifers and groups of aquifers must be distinguished (figs. 6-1 through 6-7). Previous studies (sec. 2.1) have grouped the NERB's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units (Lewis and Hotchkiss, 1981; Thamke and others, 2014). The hydrostratigraphy developed for this study is based on previous regional assessments and is summarized in plate 2, in hydrostratigraphic charts (figs. 7-2 and 7-8), and in chapter 7. The hydrostratigraphic charts in figures 7-2 and 7-8 detail the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering and others, 2007). Appendix A describes the geologic units used to develop the surface hydrogeology map (pl. 2).

Section 5.2 discusses how the map units of Love and Christiansen (1985), compiled into a Geographic Information Systems (GIS) database by the U.S. Geological Survey (USGS) and Wyoming State Geological Survey (WSGS), were used to develop plate 2. Love and Christiansen (1985), however, were unable to distinguish all stratigraphic units present due to the sheer size of the dataset, cartographic limitations, and stratigraphic complexity. Thus, not all geologic units are differentiated on their map. Further, the large number of hydrostratigraphic units in the NERB (chap. 7, pl. 2) make it impractical to calculate recharge for each unit. Instead, the WSGS aggregated the numerous stratigraphic units by geologic age and hydrostratigraphy and then generated GIS shapefiles to calculate recharge volumes and rates. WSGS generally followed the classifications used by the USGS (Thamke and others, 2014; Long and others, 2014):

- Quaternary aquifers (fig. 6-1)
- Lower Tertiary aquifer system (fig. 6-2)
- High Plains aquifer system (fig. 6-3)
- Upper Cretaceous aquifer system (fig. 6-4)
- Other Cretaceous aquifers (fig. 6-5)
- Paleozoic aquifers (fig. 6-6)
- Precambrian units (fig. 6-7)

6.2 AVERAGE ANNUAL RECHARGE

Because of evapotranspiration and natural discharge to streams, springs, lakes, and wetlands, only a fraction of the groundwater stored in the NERB can be withdrawn for beneficial use. Under natural conditions, a state of dynamic equilibrium exists where natural discharges to surface waters and evapotranspiration are balanced by recharge. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge. Withdrawals from wells and springs remove groundwater from aquifer storage and diminish natural discharges, most notably, streamflows. Thus, without careful management, riparian ecosystems will collapse and surface water rights holders will not receive their full appropriation, because over time, groundwater discharges to springs, streams, and wetlands will be depleted. This risk has long been recognized by Wyoming's agricultural community, water resource professionals, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and some of Wyoming's interstate water compacts, such as the Amended Bear River Compact of 1978 and 2001 Modified North Platte River Decree. Barlow and Leake (2012) provide an explanation of the connection of groundwater and surface water (https://pubs.er.usgs.gov/publication/cir1376).

To evaluate recharge on a regional scale, this study combines estimated average annual recharge data from the WSGS statewide recharge study (Taboga and Stafford, 2016) with maps illustrating where important hydrogeologic units crop out in the NERB (pl. 2; figs. 6-1 through 6-7).

Valuable baseline date is generated by examining periodic water levels and average annual recharge balanced with best estimates of annual discharge (both natural and by pumping). These data help to establish benchmarks for sustained yield, namely the volume of water that can be artificially discharged without unacceptably depleting aquifer storage or natural discharges. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to constrain. Estimates of annual groundwater withdrawals and consumptive uses from the previous NERB water plans (HKM and others, 2002a, b; RESPEC, 2019a, b) and the Statewide Framework Water Plan (WWC Engineering and others, 2007) are discussed in chapter 8.

Estimated average annual recharge (fig. 5-2) in the Wyoming portion of the NERB ranges from less than one inch per year in the basin interior to more than 37 inches per year in the Bighorn Mountains (Taboga and Stafford, 2016). Mountains and foothills receive more recharge than basin lowlands due to favorable environmental attributes present in highland zones:

- Greater amounts of precipitation and more persistent snow pack (fig. 3-3)
- Vegetation that favors the accumulation of snowpack, such as trees and brush
- Thin, permeable mountain soils
- Lower rates of evapotranspiration
- Permeable exposures of upturned and weathered bedrock
- The presence of structural features that enhance recharge (e.g., faults, fractures, joints, and fault/fracture-controlled surface drainages)

Figure 6-8 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Wyoming portion of the NERB and suggests what environmental factors exert control on recharge. Recharge is most efficient in and around the Bighorn Mountains and Black Hills, and slightly higher in portions of Sheridan, Campbell, and Niobrara counties. The dataset for figure 6-8 was generated by dividing 4,000-m grid cells and assigning values for average annual aquifer recharge (fig. 5-2) and average annual precipitation (fig. 3-3) to each cell.

Average annual recharge estimates (fig. 5-2) were obtained from a WSGS model (Taboga and Stafford, 2016) that uses publicly available precipitation, land slope, and soil permeability data to calculate recharge. Total average annual precipitation has been estimated (PRISM, 2013) as 18,784,902 acre-feet for the larger NERB shown in figure 3-3 and 18,158,416 acre-feet for

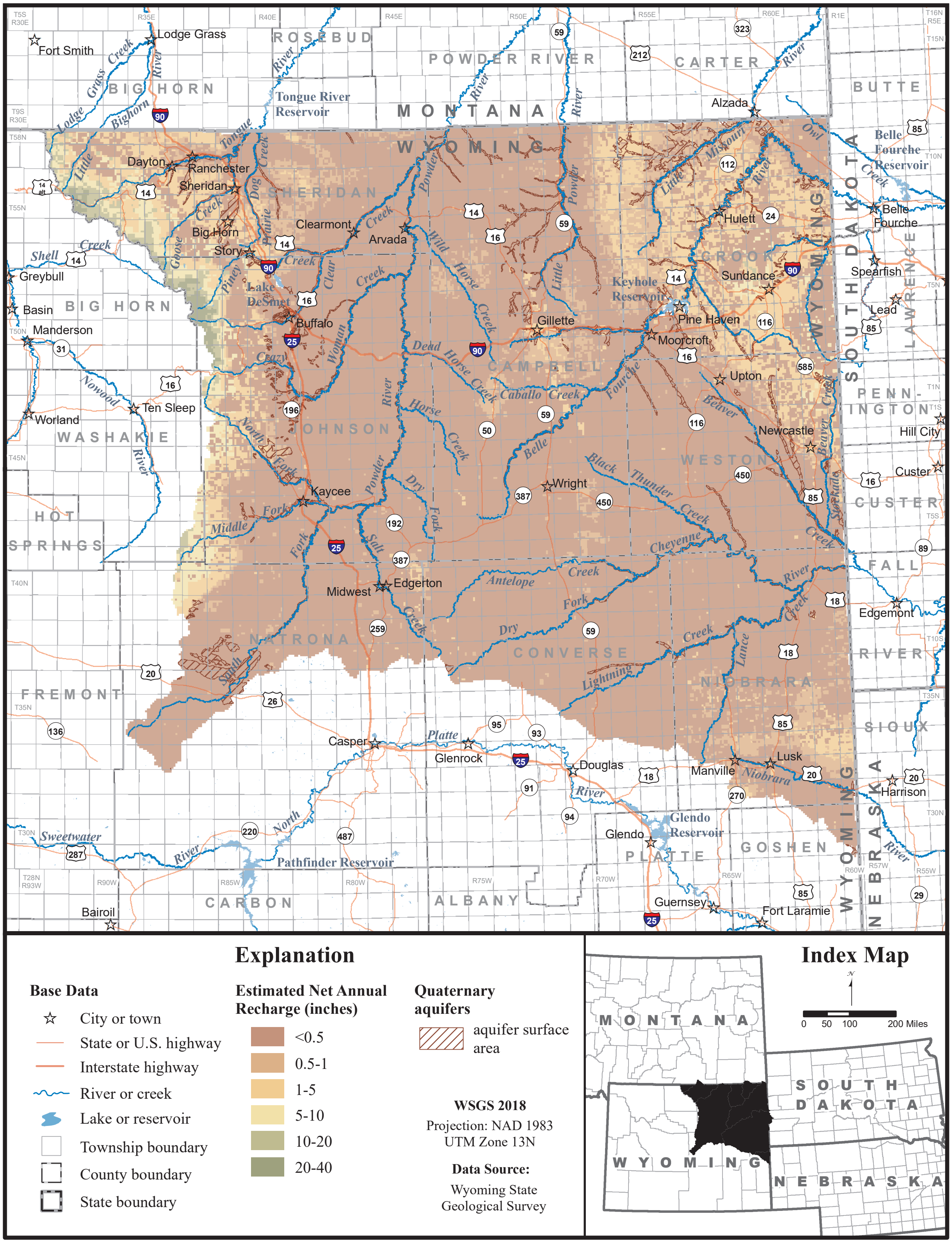


Figure 6-1. Estimated net annual aquifer recharge—surface Quaternary aquifer, NERB, Wyoming.

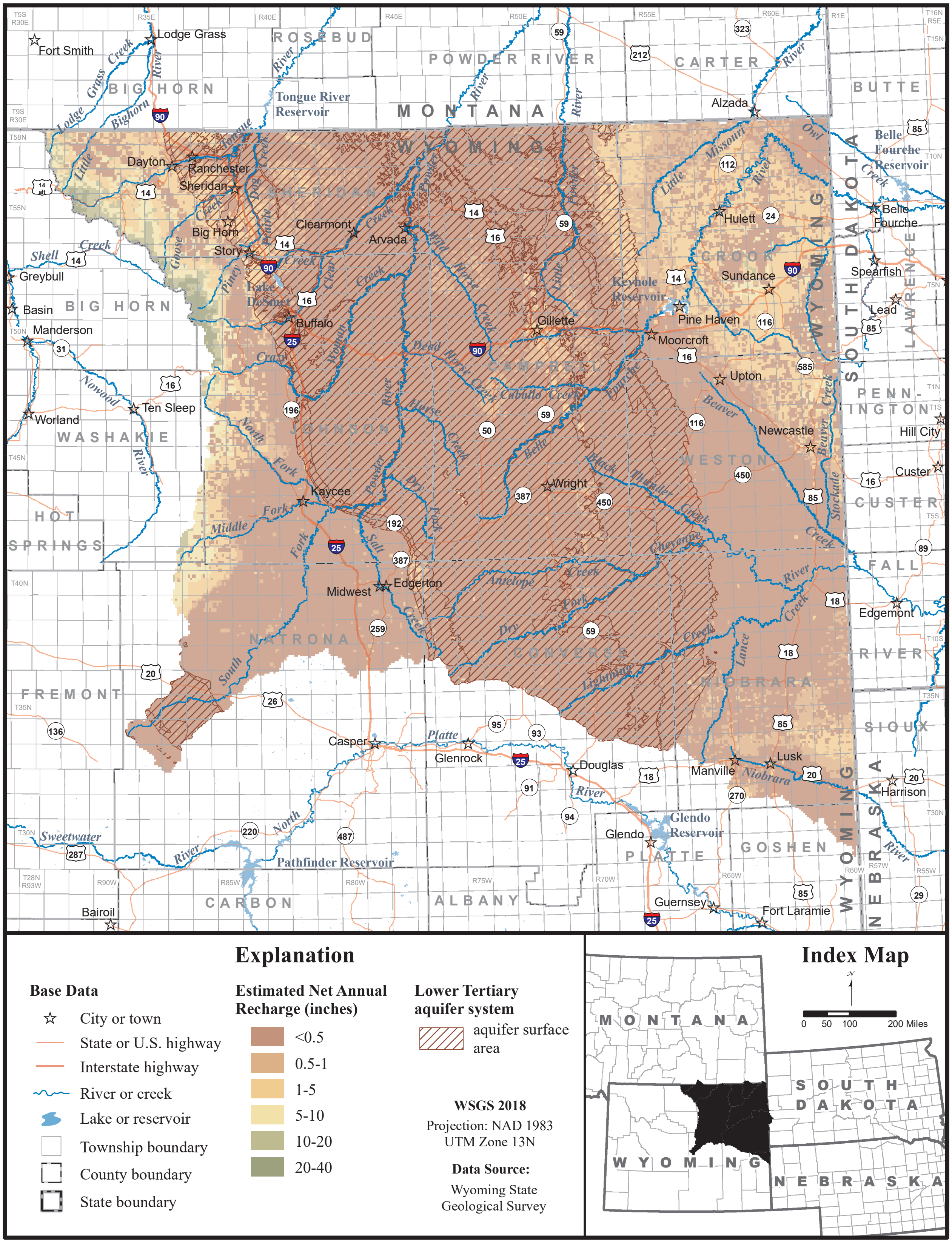


Figure 6-2. Estimated net annual aquifer recharge—surface Lower Tertiary aquifer system, NERB, Wyoming.

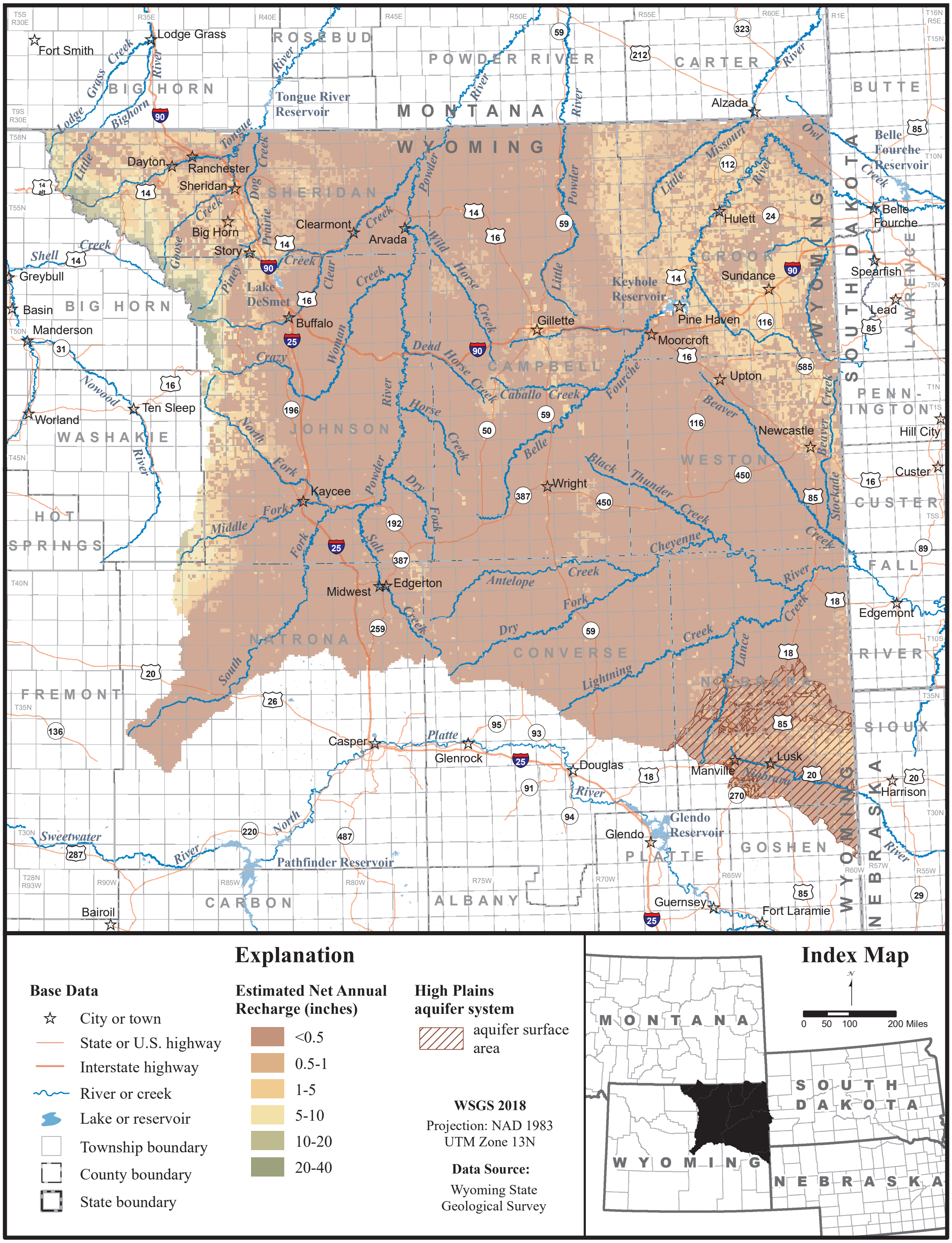


Figure 6-3. Estimated net annual aquifer recharge—surface High Plains aquifer system, NERB, Wyoming.

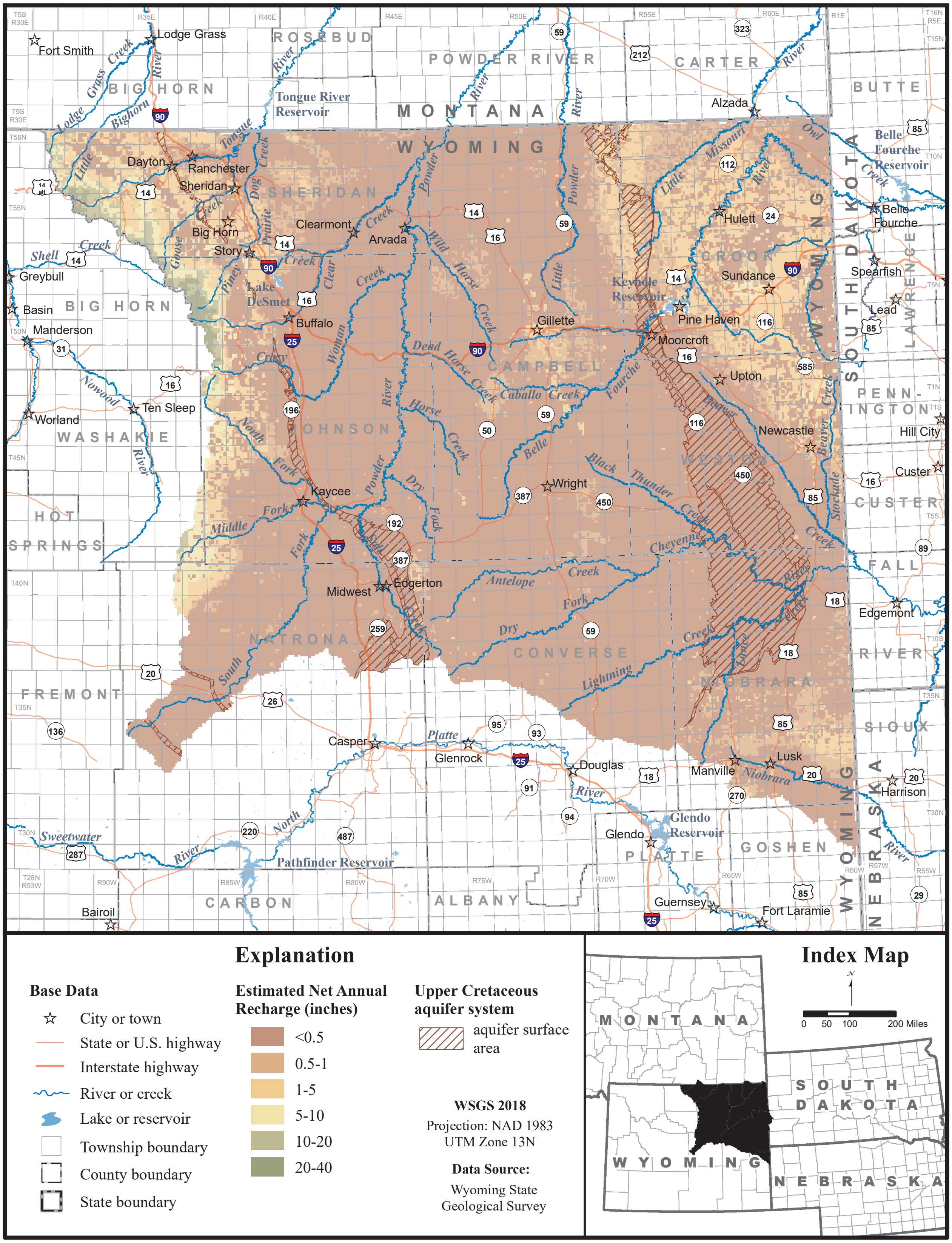


Figure 6-4. Estimated net annual aquifer recharge—surface Upper Cretaceous aquifer system, NERB, Wyoming.

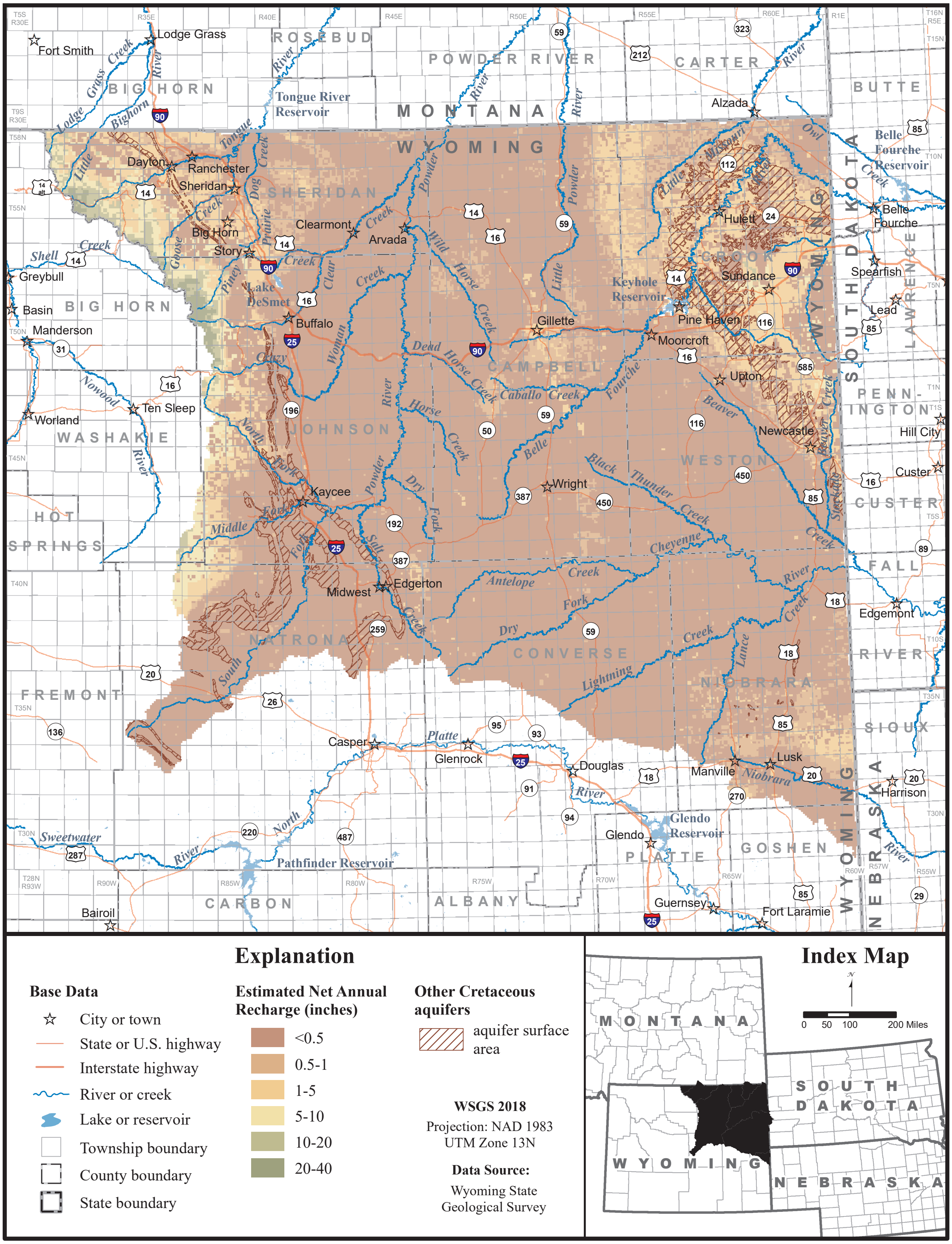


Figure 6-5. Estimated net annual aquifer recharge—surface Other Cretaceous aquifers, NERB, Wyoming.

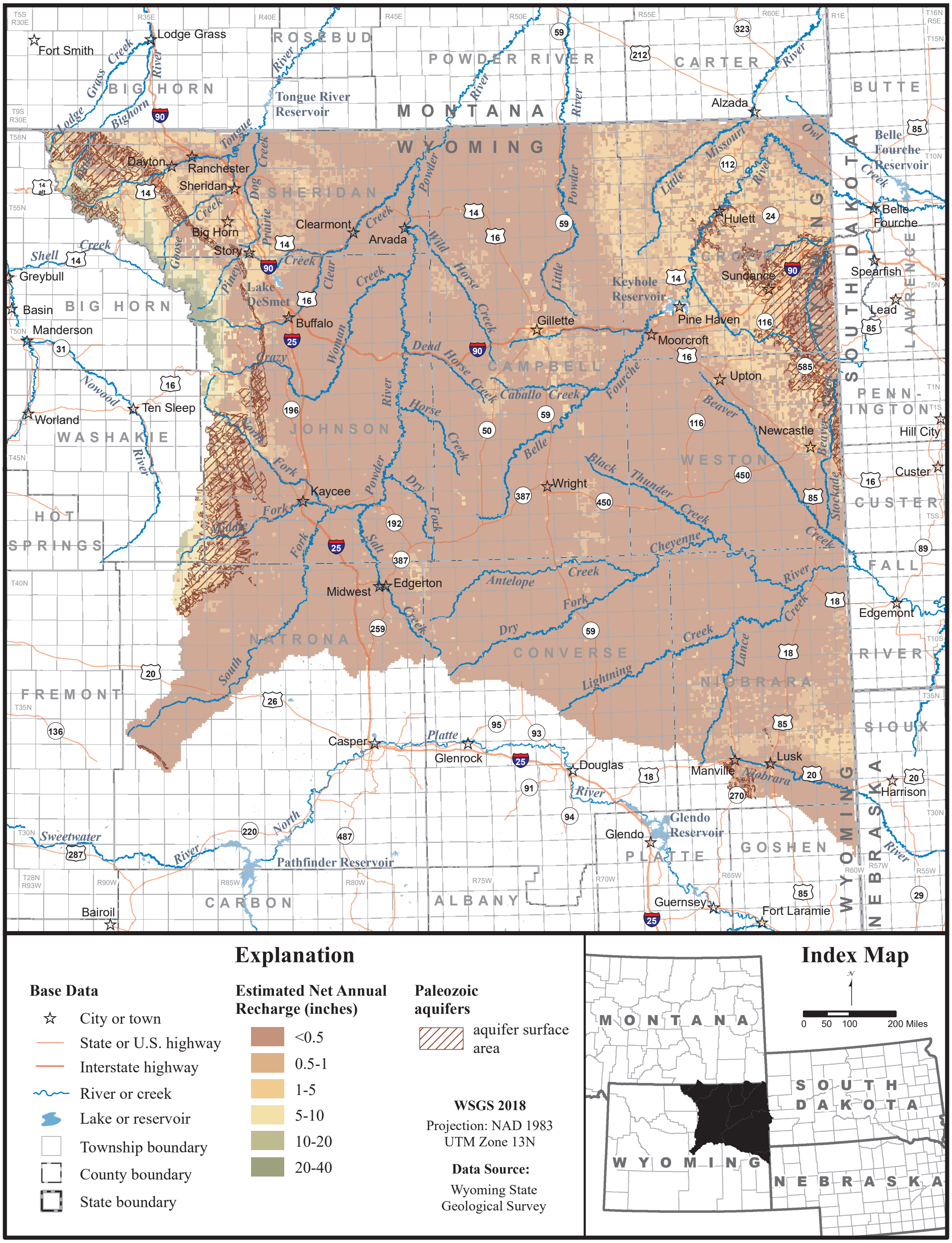


Figure 6-6. Estimated net annual aquifer recharge—surface Paleozoic aquifer, NERB, Wyoming.

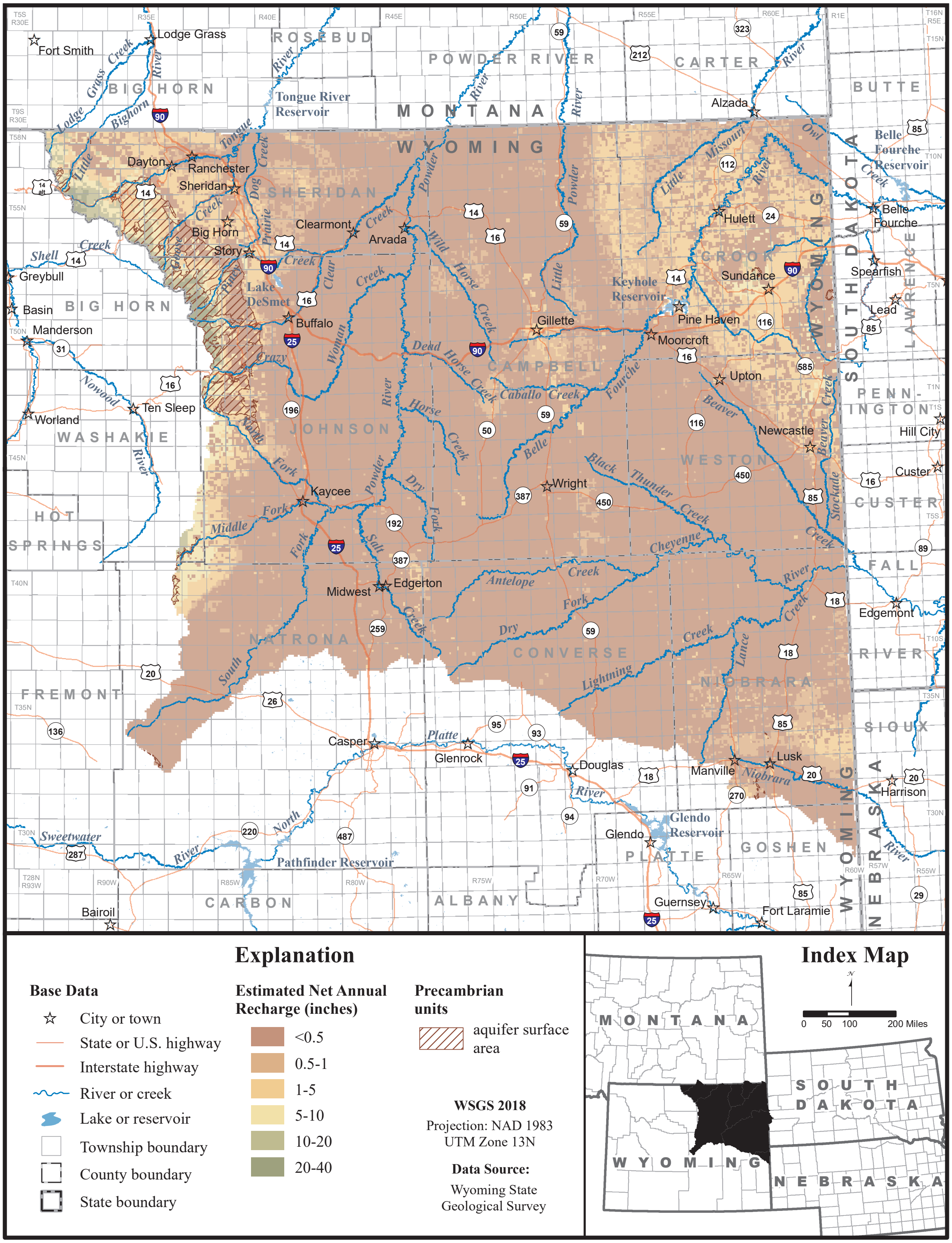


Figure 6-7. Estimated net annual aquifer recharge—surface Precambrian units, NERB, Wyoming.

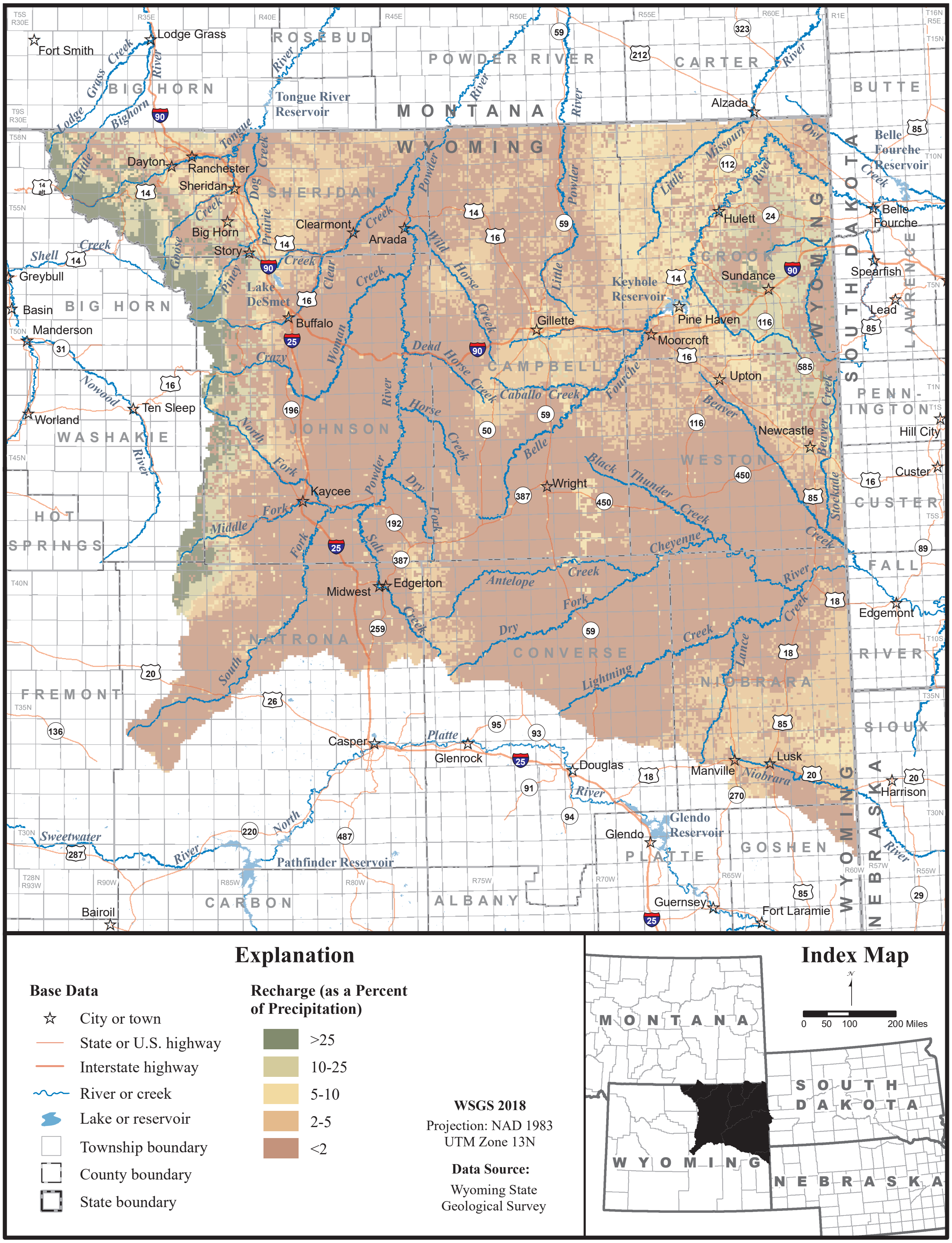


Figure 6-8. Aquifer recharge as percentage of precipitation using 1981–2010 precipitation normals, NERB, Wyoming.

the Wyoming portion exclusively (table 8-2a). Although this approach does not fully consider all factors that affect recharge, initial infiltration and precipitation levels are generally the most important factors on a regional scale. Consideration of the other factors listed above and in section 5.1.3.1 should confirm the general pattern of recharge efficiency displayed in figure 6-8. However, as discussed previously (secs. 5.1.3.1 and 5.4), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability, permeable outcrops such as scoria). Lastly, the WSGS Recharge Model (Taboga and Stafford, 2016) indicated some areas in the basin interior receive no recharge (figure 5-2).

Table 6-1 shows the percentage of surface area by specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the seven classified aquifer recharge zones (pl. 2, figs. 6-1 through 6-7).

Table 6-1 shows that Quaternary, Tertiary, and Upper Cretaceous aquifers receive recharge at efficiencies of less than 5 percent of precipitation. In contrast, Paleozoic, Precambrian, and Lower Cretaceous aquifers receive recharge at efficiencies of 5 percent or greater, likely due to these aquifers being exposed in upland areas. The consistently low recharge efficiencies calculated for Upper Cretaceous, Tertiary, and Quaternary aquifer zones likely reflect the greater aridity (fig. 3-3) within the interior of the NERB.

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

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

Surface exposures assigned to aquifer groups in the recharge calculations (figs. 6-1 through 6-7) were determined from the hydrogeologic map (pl. 2) developed for this study. Average annual rates of recharge throughout the NERB (mapped in 800-m cells) are shown in figure 5-2. Recharge rates were grouped into the five ranges to make figure 6-8 more readable and to mitigate uncertainties associated with the recharge calculations. Recharge rates for the aquifer recharge zones, mapped as polygons, were converted from inches to feet, and the average annual recharge volumes (in acre-feet) were calculated using the equation above.

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

Table 6-1. Aquifer recharge efficiencies, in percentages, for aquifers grouped by geologic age.

Recharge efficiency as annual recharge / annual precipitation, (in percentage)	0-2%	2%-5%	5%-10%	10%-25%	>25%
Quaternary	65.14%	19.30%	11.32%	3.98%	0.26%
Lower Tertiary System	74.58%	19.36%	5.31%	0.73%	0.03%
High Plains System	32.99%	54.08%	11.59%	1.34%	0.00%
Upper Cretaceous System	80.33%	13.21%	6.10%	0.36%	0.00%
Other Cretaceous Aquifers	32.67%	12.80%	18.16%	25.05%	11.32%
Paleozoic Aquifers	41.06%	4.02%	7.39%	33.93%	13.60%
Precambrian Units	30.77%	5.58%	6.68%	19.66%	37.32%

Table 6-2 summarizes calculated recharge for the NERB over the ranges of average annual recharge mapped on figure 5-2 alongside the aquifer recharge zones displayed in figures 6-1 through 6-7. A "best total" amount for each range of recharge over the exposed area of each aquifer group is provided in tables 6-2 and 6-3, and is based on the recharge area for each whole inch of recharge in the database compiled for this study. The "best total" is calculated directly from the detailed cell-by-cell recharge data and the corresponding surface area.

Table 6-3 summarizes calculated average annual recharge statistics from the more detailed calculations provided in table 6-2. Additionally, table 6-3 provides a "best total" average recharge depth delivered over the entire surface area of each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Precambrian aquifers receive 0.73 ft (8.8 in) of recharge compared to about 0.95 and 0.6 in, respectively, in Quaternary and Tertiary (lower Tertiary system and High Plains aquifer combined). The Upper Cretaceous aquifer system, which

Table 6-2. NERB average annual recharge calculations (Taboga and Stafford, 2016; PRISM, 2013).

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Quaternary aquifers	0.0	0.00	103,431	3,393
	0.5	0.04		
	0.5	0.04	72,467	4,755
	1.0	0.08		
	1.0	0.08	69,267	9,695
	5.0	0.42		
	5.0	0.42	3,858	1,837
	10.0	0.83		
	10.0	0.83	0.00	0.00
	20.0	1.67		
	20.0	1.67	0.00	0.00
	40.0	3.33		
TOTAL			**249,022**	**19,680**

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Lower Tertiary aquifer system	0.0	0.00	1,700,210	55,781
	0.5	0.04		
	0.5	0.04	525,640	34,491
	1.0	0.08		
	1.0	0.08	238,174	29,292
	5.0	0.42		
	5.0	0.42	2,890	1,543
	10.0	0.83		
	10.0	0.83	0	0
	20.0	1.67		
	20.0	1.67	0	0
	40.0	3.33		
TOTAL			**2,466,913**	**121,106**

Table 6-2. continued

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
High Plains aquifer system	0.0	0.00	362,483	11,893
	0.5	0.04		
	0.5	0.04	153,856	10,096
	1.0	0.08		
	1.0	0.08	60,609	6,686
	5.0	0.42		
	5.0	0.42	0	0
	10.0	0.83		
	10.0	0.83	0	0
	20.0	1.67		
	20.0	1.67	0	0
	40.0	3.33		
TOTAL			**576,948**	**28,674**

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Upper Cretaceous aquifer system	0.0	0.00	253,523	8,318
	0.5	0.04		
	0.5	0.04	72,275	4,742
	1.0	0.08		
	1.0	0.08	47,840	5,391
	5.0	0.42		
	5.0	0.42	0	0
	10.0	0.83		
	10.0	0.83	0	0
	20.0	1.67		
	20.0	1.67	0	0
	40.0	3.33		
TOTAL			**373,638**	**18,451**

Table 6-2. continued

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best Total (acre-feet)
Other Cretaceous aquifers	0.0	0.00	37,903	1,244
	0.5	0.04		
	0.5	0.04	53,465	3,508
	1.0	0.08		
	1.0	0.08	265,172	45,054
	5.0	0.42		
	5.0	0.42	9,269	4,652
	10.0	0.83		
	10.0	0.83	0	0
	20.0	1.67		
	20.0	1.67	0	0
	40.0	3.33		
TOTAL			**365,809**	**54,458**

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Paleozoic aquifers	0.0	0.00	28,997	951
	0.5	0.04		
	0.5	0.04	27,401	1,798
	1.0	0.08		
	1.0	0.08	331,241	80,608
	5.0	0.42		
	5.0	0.42	104,264	56,793
	10.0	0.83		
	10.0	0.83	30,283	36,158
	20.0	1.67		
	20.0	1.67	8,204	14,753
	40.0	3.33		
TOTAL			**530,390**	**191,062**
NERB TOTAL ***(recharge for sedimentary aquifers)***			**4,562,721**	**433,431**

Table 6-2. continued

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Precambrian units	0.0	0.00	14,939	490
	0.5	0.04		
	0.5	0.04	16,240	1,066
	1.0	0.08		
	1.0	0.08	99,473	24,272
	5.0	0.42		
	5.0	0.42	96,752	59,535
	10.0	0.83		
	10.0	0.83	57,973.47	69,721.47
	20.0	1.67		
	20.0	1.67	40812.75	84,229.63
	40.0	3.33		
TOTAL			**326,190**	**239,313**

is exposed in highland areas located primarily in northern and central parts of the basin (pl. 2), receives 0.05 ft (~0.59 in) of recharge. Infiltration through Paleozoic and volcanic strata provides about 64 percent of the basin's recharge.

In the Wyoming part of the NERB, the best estimate of total recharge is 672,744 acre-feet, or about 4 percent of total precipitation.

6.3 SUMMARY

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the entire NERB (fig. 3-2) has been estimated as 18,784,902 acre-feet, with 18,158,416 acre-feet being the estimated Wyoming portion (table 8-2a).
- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the NERB ranges up to 37 in (Taboga and Stafford, 2016), with the lowest values occurring in the interior basins and the highest values in the upland drainages of the surrounding mountain ranges.
- Other factors controlling recharge may dominate locally (e.g., solution enhanced fractures). However, consideration of these factors should confirm the overall pattern of recharge and recharge efficiency.
- Recharge from precipitation to flat-lying Tertiary and Quaternary aquifers in the interior basin is generally less efficient than recharge to the exposed Paleozoic aquifers and Precambrian units in the mountainous areas. Recharge in the NERB is most efficient in higher elevation, Paleozoic terrains.
- Estimates of average annual recharge in the NERB are presented as a "best total" based on the cell-by-cell product of area and rate of recharge.

Table 6-3. Annual recharge statistics for NERB aquifer recharge zones (PRISM, 2013; Taboga and Stafford, 2016).

Aquifer recharge zone	Recharge zone surface area (acres)	Percentage of total basin surface area	"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth (feet)	"Best total" average recharge depth (inches)
Quaternary	249,022	5.09%	19,680	2.93%	0.079	0.95
Lower Tertiary System	2,466,913	50.46%	121,106	18.00%	0.049	0.59
High Plains System	576,948	11.80%	28,674	4.26%	0.050	0.60
Upper Cretaceous System	373,638	7.64%	18,451	2.74%	0.049	0.59
Other Cretaceous Aquifers	365,809	7.48%	54,458	8.09%	0.149	1.79
Paleozoic Aquifers	530,390	10.85%	191,062	28.40%	0.360	4.32
Precambrian Units	326,190	6.67%	239,313	35.57%	0.734	8.80
Total, Precambrian through Quaternary zones	**4,888,911**	**100.00%**	**672,744**	**100.00%**	**0.138**	**1.65**
Total, Sedimentary Aquifers (Paleozoic through Quaternary zones)	**4,562,721**	**75%**	**433,431**	**28%**	**0.057**	**0.68**

Chapter 7

Physical and chemical characteristics of hydrogeologic units in the Powder/Tongue/Northeast River Basins (NERB)

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

7.1 NORTHEASTERN RIVER BASINS

Most of the geographic extent of the Northeastern River Basins (NERB) study area is contained within the boundary of the Northern Great Plains aquifer system, a large regional (multi-state) aquifer system present in parts of northeastern Wyoming, central and eastern Montana, most of North and South Dakota, a small part of northwestern Nebraska, and part of Canada (fig. 7-1; Downey, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996, fig. 49). Within the NERB study area, the Northern Great Plains aquifer system includes most sedimentary strata located in the Powder River structural basin (PRSB), Black Hills uplift area, eastern flank of the Bighorn Mountains, and part of the Casper arch (fig. 7-1). Strata of the Northern Great Plains aquifer system in the NERB study area consists of most Tertiary-age sedimentary lithostratigraphic units and all Paleozoic- and Mesozoic-age sedimentary lithostratigraphic units grouped into various hydrogeologic units (aquifers and confining units) and aquifer systems (fig. 7-2). The Northern Great Plains aquifer system contains most of the hydrogeologic units in the NERB study area, and thus, most of this chapter consists of identification and description of hydrogeologic units contained in this system. These hydrogeologic units are identified and the physical and chemical characteristics grouped together and described separately from those within the NERB study area boundary that are not part of the aquifer system.

The NERB study area also includes small parts of the Hartville uplift and adjacent areas and the Wind River structural basin (WRSB) (fig. 7-1). Water-saturated and permeable Tertiary-age lithostratigraphic units composed of sedimentary rocks in and surrounding the Hartville uplift form part of the regional High Plains rather than Northern Great Plains aquifer system (Whitehead, 1996; see areal extent of High Plains aquifer system in relation to NERB study area boundary in fig. 7-1). Hydrogeologic units in the Wind River structural basin composed of water-saturated and permeable Tertiary- to Paleozoic-age sedimentary rocks are not considered part of the Northern Great Plains aquifer system (Downey, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996); consequently, these hydrogeologic units are identified and the physical and chemical characteristics described separately from those associated with the Northern Great Plains aquifer system. Hydrogeologic units in the WRSB part of the NERB study area are identified in the text herein with a parenthetical "Wind River structural basin" after the name of the hydrogeologic unit to differentiate them from similar units that are part of the Northern Great Plains aquifer system. Summaries of physical and chemical characteristics of hydrogeologic units in the WRSB presented in figures and tables and on plates are similarly differentiated from those that are considered part of the Northern Great Plains aquifer system. Because of limited geographic extent in the study area, only selected hydrogeologic units in the Hartville uplift and WRSB for which physical or chemical characteristics were available are identified and described herein. All hydrogeologic units in both areas were identified and extensively described in the most recent versions of the Platte River and Wind/Bighorn River Basin Plans (Taucher and others, 2012, 2013, respectively), and readers seeking additional information about the hydrogeologic units in both areas are referred to these two companion volumes to this report.

As with all other most recent versions of the Wyoming river basin plans (Clarey and others, 2010; Taucher and others, 2012, 2013; Taboga and others, 2014a, b), individual hydrogeologic units are identified and described in this chapter of the report in a somewhat standalone manner so interested readers can consult only the unit(s) of interest without having to read the entire chapter. Because of this approach, individuals reading this entire chapter will encounter some degree of redundancy to facilitate the standalone "unit-oriented" organization.

In this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are summarized in tabular format (plate 3). The original sources of the data used to construct the summary are listed (see the bottom of plate 3). Locations of the springs or wells used to compile plate 3 are shown on fig. 7-3. Physical characteristics are summarized to provide a broad description 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 conducted for this study. For example, values of transmissivity derived from aquifer tests were used as published in the original reports, and no reanalysis of previously published aquifer tests was conducted.

As described in chapter 5, chemical characteristics of hydrogeologic units in the NERB study area are described using summary statistics (appendices E–H), trilinear diagrams (appendices I–L), and through comparisons with regulatory standards listed in table 5-1. Locations of the springs and wells from which this information was compiled are shown on fig. 7-4 (environmental groundwater-quality samples), fig. 7-5 (produced groundwater-quality samples), and fig. 7-6 (groundwater-quality samples from coal aquifers) in relation to the NERB study area boundary.

7.2 CENOZOIC HYDROGEOLOGIC UNITS

Hydrogeologic units composed of Cenozoic-age sedimentary (unconsolidated, semi-consolidated, and consolidated) and igneous (intrusive) rocks in the NERB study area are identified, and the physical and chemical characteristics described, in this section of the report. The areal extent of exposed Cenozoic-age lithostratigraphic and hydrogeologic units in the NERB study area is shown on plates 1 and 2, respectively.

7.2.1 Quaternary unconsolidated deposits

The physical and chemical characteristics of four different types of saturated (water-bearing) unconsolidated deposits of Quaternary age present in the NERB study area are discussed in this section of the report.

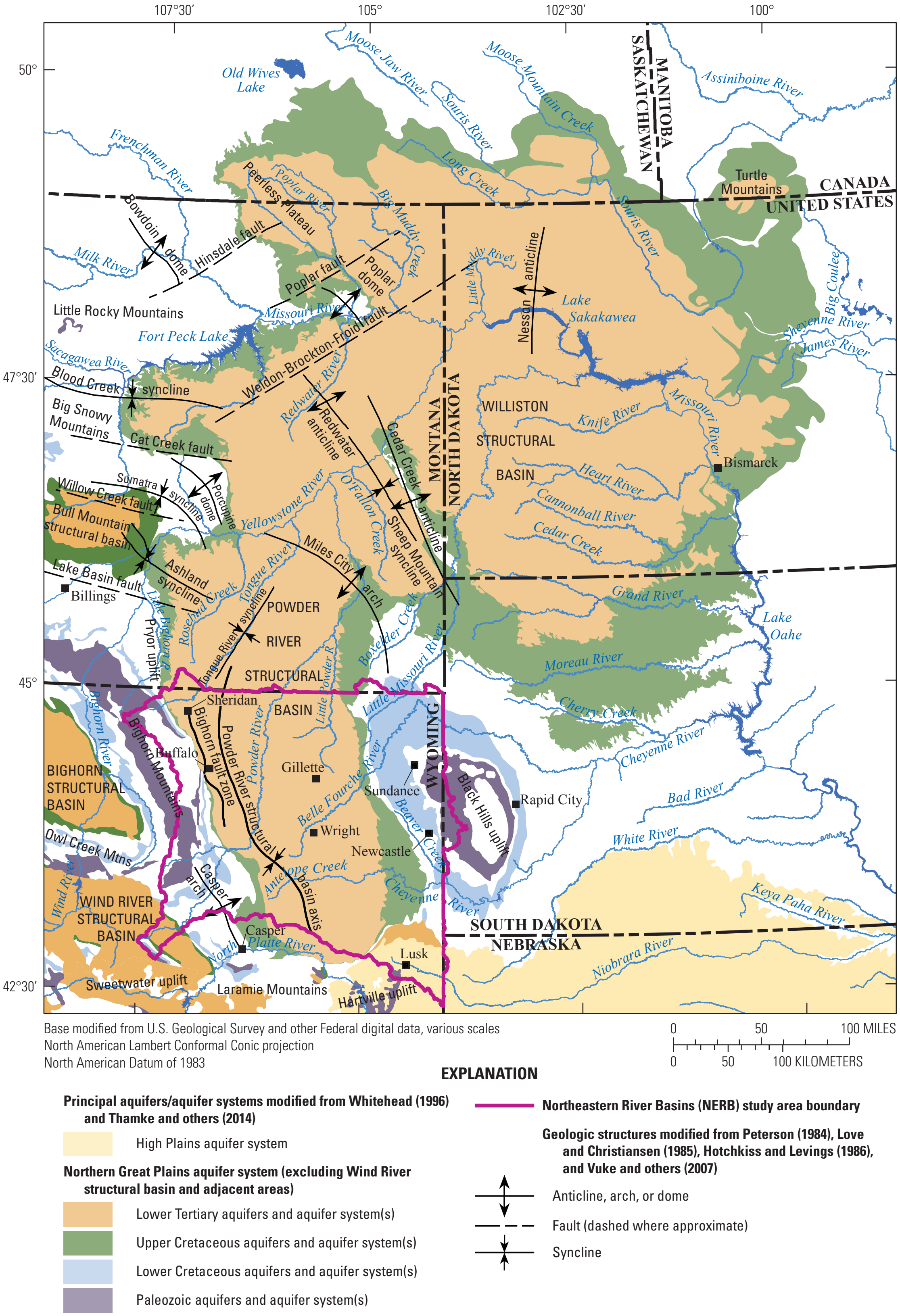
Physical characteristics

Saturated Quaternary unconsolidated deposits in the NERB study area include alluvium, terrace, dune sand (eolian), and glacial deposits (Hodson and others, 1973, sheet 3, and references therein; Feathers and others, 1981). Alluvium and terrace deposits consist of unconsolidated, poorly to well-sorted mixtures of clay, silt, sand, gravel, and cobbles deposited by and along streams. Coarser deposits such as cobbles and boulders may occur locally. Alluvium and terrace deposits are found primarily along most major and minor drainages, so geographic extent is small in comparison with the full extent of the NERB study area (plate 1). Alluvium was deposited by streamflow as channel fill and floodplain deposits along former and currently active stream channels. Terrace deposits also were deposited by streamflow, but the deposits generally are located at elevations higher than currently active stream channels and floodplains. Locally, mapped alluvium can include alluvial fan and terrace deposits, valley-side colluvium, or talus because it is difficult to differentiate between the different types of unconsolidated deposits and because some geologists interpret and map the deposits differently.

Thickness of alluvium and terrace deposits in the NERB study area is greatest near major streams and associated tributaries. Maximum thickness of alluvium and terrace deposits is 100 feet (ft) or more, but most deposits are less than 60-ft thick [Leopold and Miller, 1954; Whitcomb and Morris, 1964; Hodson and others, 1973, sheet 3, and references therein; Ground-Water Subgroup of Water Work Group, Northern Great Plains Resource Program (shortened hereinafter to "Groundwater Subgroup"), 1974; Cooley, 1978; Feathers and others, 1981; Wells, 1982; Lowry and others, 1986].

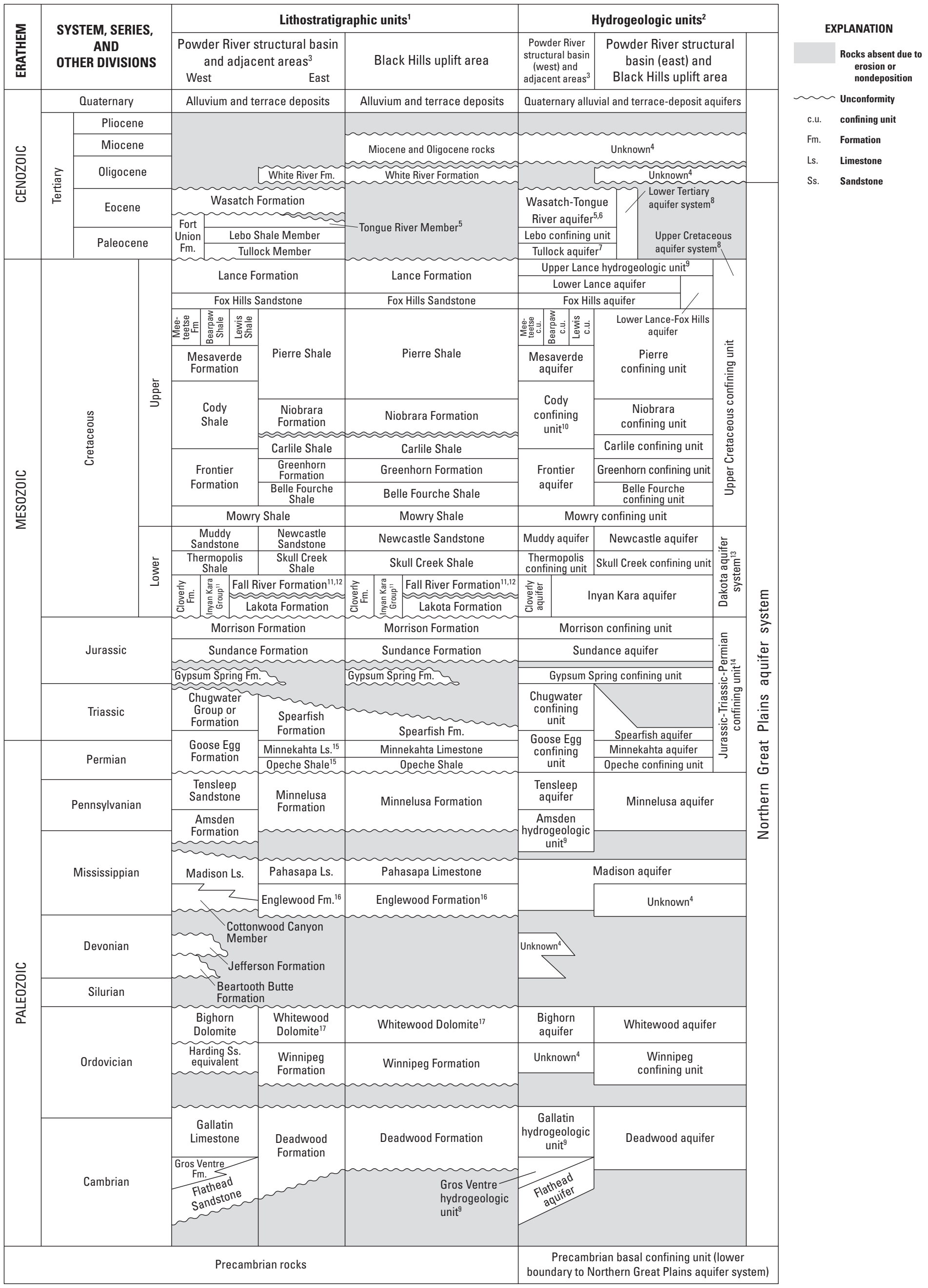
The size of sediments composing alluvium and terrace deposits is related primarily to the source of the eroded and transported parent material and the distance the sediments have been transported. Alluvium derived from material eroded from resistant Precambrian and Paleozoic rocks more common along uplift areas generally has a larger percentage of coarse-grained sediments than alluvium from parent material eroded from fine-grained rocks such as clay, shale, and fine-grained sandstone common to many of the Tertiary and Cretaceous rocks in typically flat lower-lying areas such as the center of the PRSB (Kohout, 1957; Whitcomb, 1965; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973, sheet 3; Sowers, 1979; Feathers and others, 1981). The coarsest alluvial and terrace deposits, and thus likeliest to have the greatest aquifer potential, are found in the valleys of major rivers including the Powder, Little Powder, Tongue, Cheyenne, Belle Fourche, and Little Missouri Rivers, and Lance, Crazy Woman, and Clear Creeks (fig. 7-3) (Morris, 1956; Whitcomb and Morris, 1964; Whitcomb and others, 1966; Hodson and others, 1973, sheet 3, and references therein; Cooley, 1978; Goodwin and Hasfurther, 1982; Lowry and others, 1986).

Where saturated and sufficiently permeable, alluvial and terrace deposits can contain aquifers. Most of these aquifers are found in alluvium (identified herein as Quaternary alluvial aquifers) rather than terrace deposits (Quaternary terrace-deposit aquifers). Terrace deposits in most parts of the NERB study area are drained of water (unsaturated) because they are higher than present-day stream channels and associated potential recharge (Whitcomb and others, 1966; Feathers and others, 1981; Goodwin and Hasfurther, 1982); however, terrace deposits along major streams in the western part of Sheridan County "contain significant quantities of water" (Lowry and Cummings, 1966). Small ephemeral springs and seeps may issue from the base of terrace deposits at their contact with underlying less-permeable bedrock (Whitcomb and others, 1966). Groundwater in alluvial and terrace-deposit aquifers typically is under unconfined conditions, and groundwater levels generally are close to land surface (Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973, sheet 3; Cooley, 1978; Feathers and others, 1981). Groundwater in alluvial aquifers commonly is hydraulically connected to local streams and rivers (Whitcomb and Morris, 1964; Cooley, 1978; Sowers, 1979; Goodwin and Hasfurther, 1982; Wesche, 1982; Ringen and



Base modified from U.S. Geological Survey and other Federal digital data, various scales
North American Lambert Conformal Conic projection
North American Datum of 1983

Figure 7-1. Northeastern River Basins study area in relation to the principal aquifers and aquifer systems of the Northern Great Plains and adjacent areas that are exposed at the land surface.



[1] Compiled from Love and others (1993), Macke (1993), and Wyoming Geological Association (2014).

[2] Compiled or modified primarily from Whitcomb and Morris (1964); Hodson and others (1973, and references therein); Wyoming State Engineer's Office (1974); Huntoon (1976); Old West Regional Commission (1976); Feathers and others (1981); Lewis and Hotchkiss (1981); Western Water Consultants, Inc. (1982a,b, 1983); Downey (1984, 1986); Hotchkiss and Levings (1986); Kyllonen and Peter (1987); Downey and Dinwiddie (1988); Whitehead (1996); Strobel and others (1999); and Thamke and others (2014).

[3] "Adjacent areas" includes the eastern flank of the Bighorn Mountains and part of the Casper arch area adjacent to the Powder River structural basin.

[4] "Unknown" indicates information is not sufficient to classify lithostratigraphic unit as a hydrogeologic (hydrostratigraphic) unit (aquifer or confining unit).

[5] Includes Wyodak-Anderson coal zone and associated aquifer (fig. 7–8).

[6] Wasatch-Tongue River aquifer can include water-saturated and permeable sandstone in upper part of the underlying Lebo Shale Member and water-saturated and permeable Quaternary alluvium in some local areas (Lewis and Hotchkiss, 1981).

[7] Tullock aquifer can contain water-saturated and permeable sandstone in the basal part of the overlying Lebo Shale Member (Lewis and Hotchkiss, 1981).

[8] See fig. 7–8 for additional/alternative hydrostratigraphic classification of lithostratigraphic units composing the lower Tertiary and Upper Cretaceous aquifer systems.

[9] "Hydrogeologic unit" classification indicates part of the lithostratigraphic unit may act as a confining unit in some areas and as an aquifer in other areas because of spatially variable characteristics.

[10] Sandstone beds in Shannon and Sussex Members (not shown) may contain aquifers.

[11] Some studies identify a shale interval below the Fall River Formation in parts of the study area. This shale interval has been classified as a formation (Fuson Shale) in some studies, but this lithostratigraphic unit designation is not formally recognized in many studies.

[12] Fall River Formation is alternatively identified as the "Dakota," commonly in the subsurface where the unit contains petroleum in the eastern and central Powder River structural basin. The name is still used locally and informally, even though "Dakota" is a formally recognized name for a regionally extensive lithostratigraphic unit in North and South Dakota known as the Dakota Formation/Sandstone (stratigraphically equivalent to the Muddy and Newcastle Sandstones in Wyoming).

[13] Also known as Lower Cretaceous aquifer system (Downey and Dinwiddie, 1988).

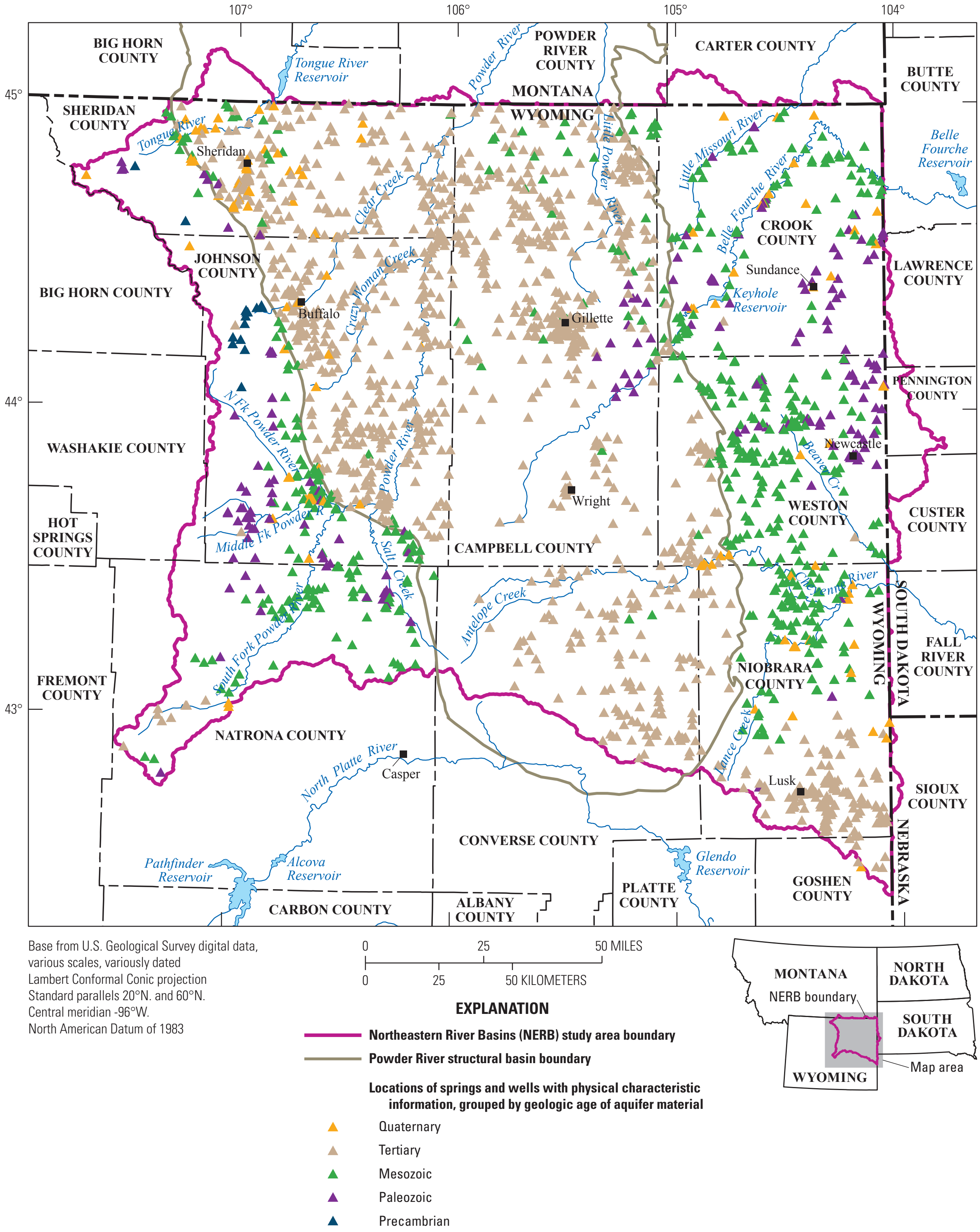
[14] Water-saturated and permeable sandstone beds in some of the lithostratigraphic units identified as confining units composing the Jurassic-Triassic-Permian confining unit may contain local aquifers.

[15] Minnekahta Limestone and Opeche Shale considered members of the Goose Egg Formation in some studies.

[16] Age of basal part of Englewood Formation is unclear with interpretations of Late Devonian or Early Mississippian age. See Macke (1993) for discussion.

[17] Commonly grouped with and (or) identified as Red River Formation in regional studies.

Figure 7-2. Hydrostratigraphic diagram showing lithostratigraphic and corresponding hydrogeologic units, Powder River structural basin and adjacent areas and Black Hills Uplift area within the Northeastern River Basins study area, Wyoming.



Base from U.S. Geological Survey digital data,
various scales, variously dated
Lambert Conformal Conic projection
Standard parallels 20°N. and 60°N.
Central meridian -96°W.
North American Datum of 1983

Figure 7-3. Locations of springs and wells with physical characteristic information, grouped by geologic age of aquifer material, Northeastern River Basins study area, Wyoming.

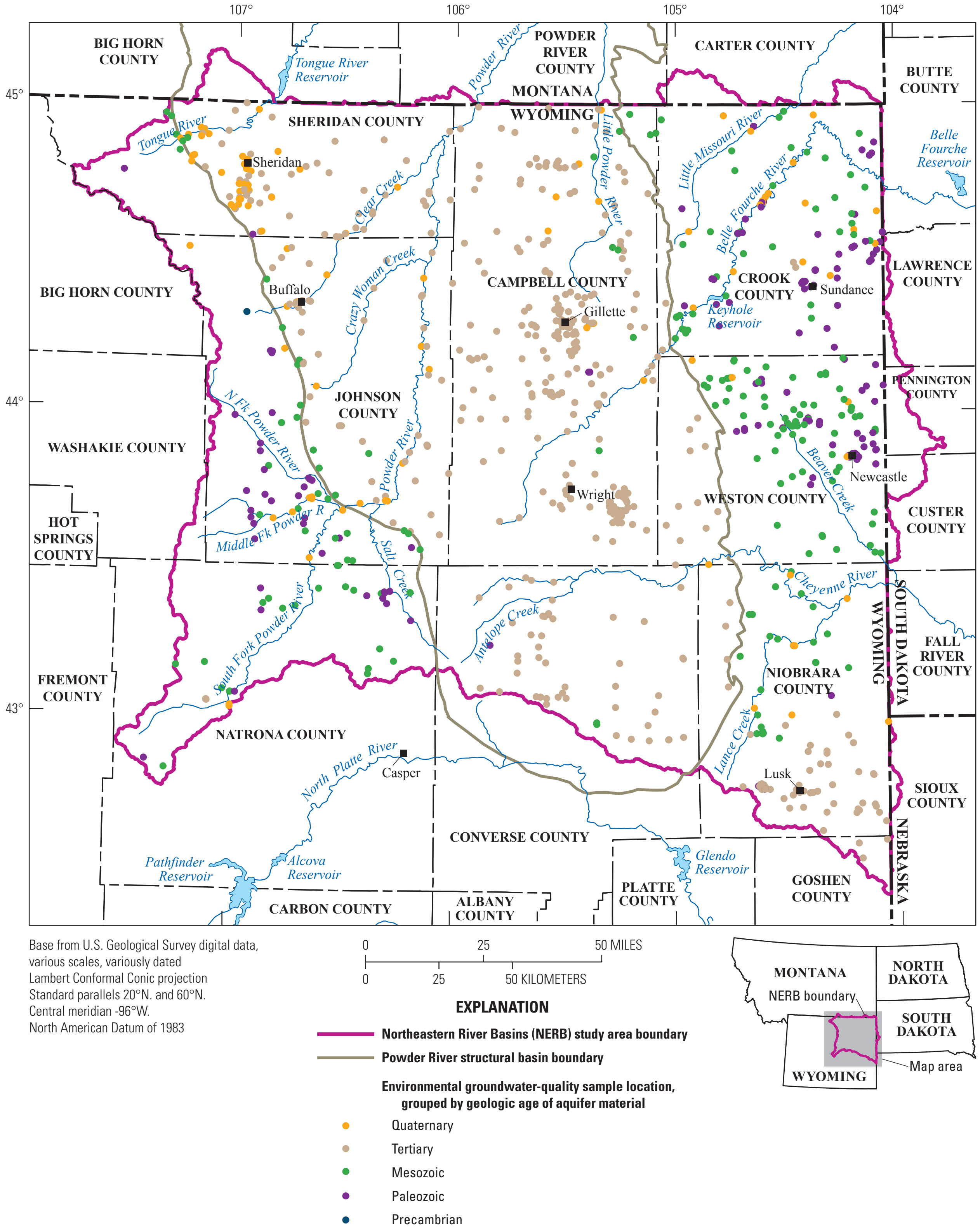


Figure 7-4. Environmental groundwater-quality sample locations, grouped by units of geologic age of aquifer material, Northeastern River Basins study area, Wyoming.

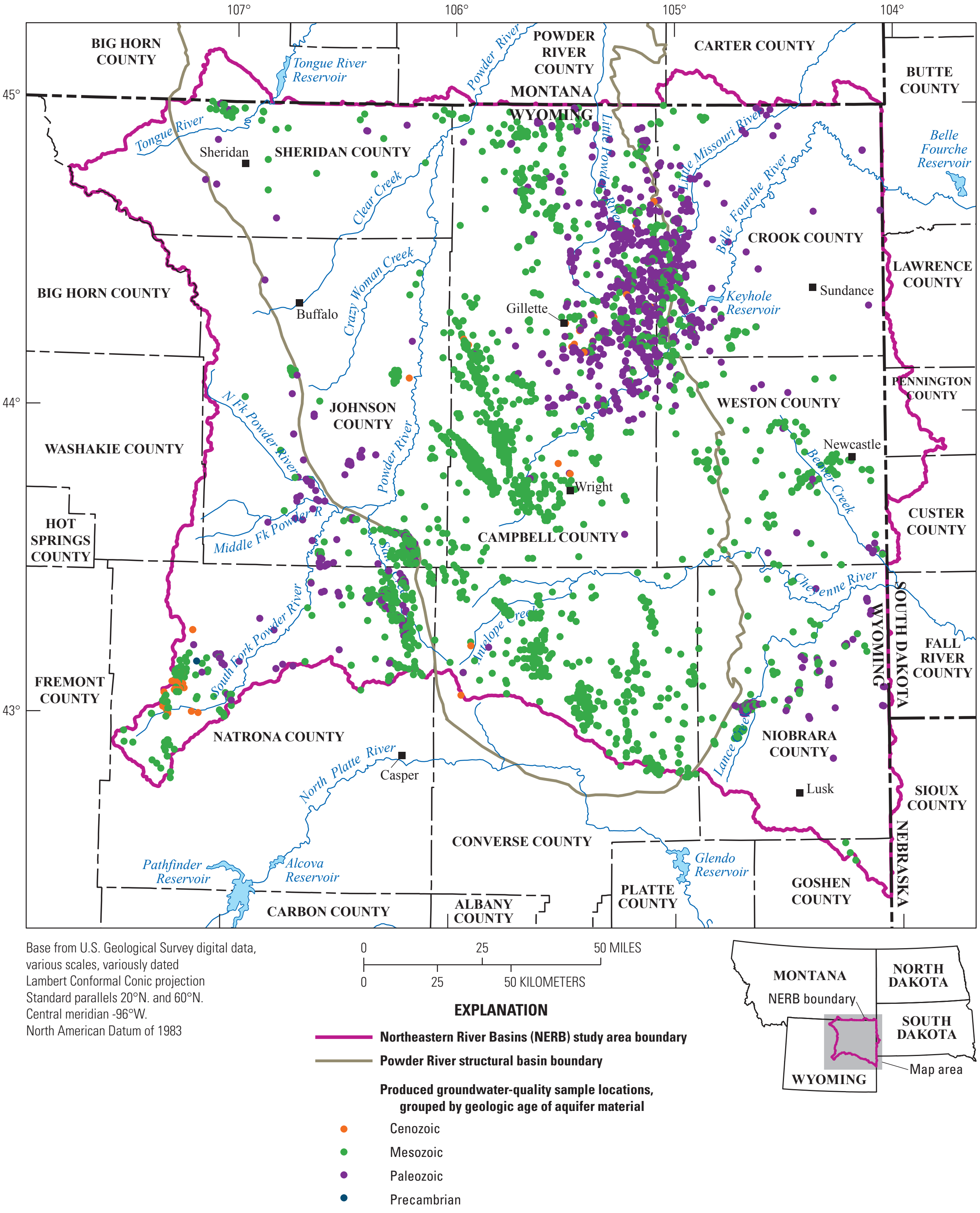
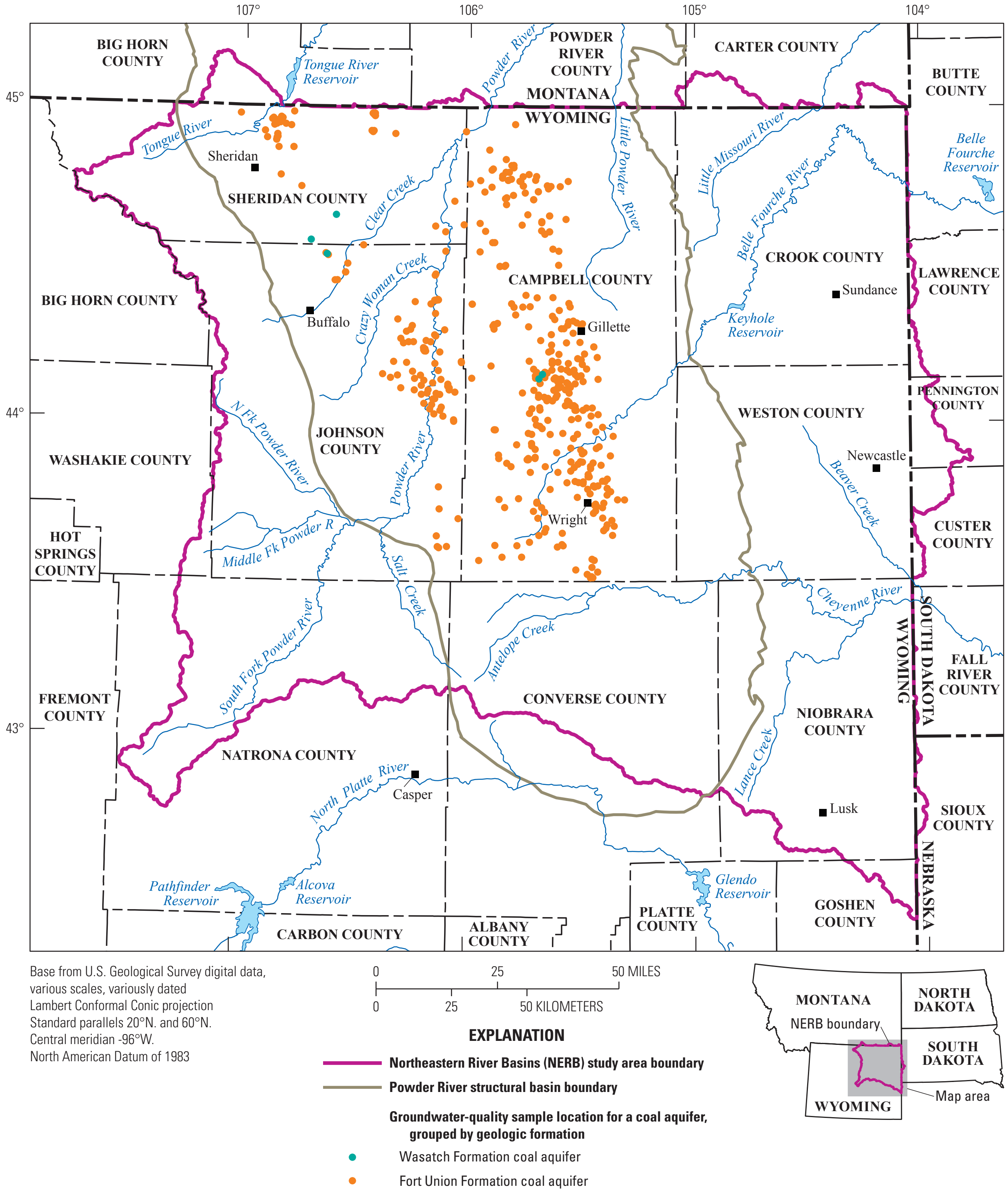


Figure 7-5. Produced groundwater-quality sample locations, grouped by geologic age of aquifer material, Northeastern River Basins study area, Wyoming.



Base from U.S. Geological Survey digital data,
various scales, variously dated
Lambert Conformal Conic projection
Standard parallels 20°N. and 60°N.
Central meridian -96°W.
North American Datum of 1983

Figure 7-6. Coal aquifer groundwater-quality sample locations in the Powder River structural basin, grouped by geologic formation, Northeastern River Basins study area, Wyoming.

Daddow, 1990). Water obtained from Quaternary alluvial and terrace-deposit aquifers is used most commonly for livestock and domestic purposes, and less commonly for irrigation purposes (HKM Engineering, Inc., and others, 2002a, b).

Quaternary alluvial aquifers are in hydraulic connection with underlying bedrock aquifers in many areas (Whitcomb, 1965; Whitcomb and others, 1966; Cooley, 1978; Feathers and others, 1981; Stock, 1981); however, this is likely not the case everywhere in the NERB study area. For example, Ringen and Daddow (1990) studied the hydrology of the stream/aquifer system consisting of the Powder River and associated alluvium between Sussex, Wyoming, and Moorhead, Montana. The investigators concluded that hydraulic connection between the Powder River stream/aquifer system and the bedrock of the underlying Wasatch and Fort Union Formations was minimal, at least in the areas examined.

Hydrogeologic data describing the Quaternary alluvial and terrace-deposit aquifers in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3. Well yields and aquifer physical properties vary substantially, reflecting the variable sediment size and sorting, as well as variable saturated thickness of an unconfined aquifer that changes in response to aquifer recharge and water withdrawal (Whitcomb and Morris, 1964; Crist and Lowry, 1972; Hodson and others, 1973, sheet 3).

Recharge to Quaternary alluvial and terrace-deposit aquifers is from direct precipitation on the deposits, ephemeral and perennial streamflow losses, infiltrating irrigation water, and groundwater seepage from underlying and adjacent hydrogeologic units (Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Sowers, 1979; Stephenson, 1982; Ringen and Daddow, 1990). Irrigation is a major source of recharge to alluvial and terrace-deposit aquifers in the Sheridan area (Lowry and Cummings, 1966). Recharge to alluvial aquifers from streamflow (streamflow loss) is greatest during high river stage (Whitcomb and Morris, 1964; Whitcomb and others, 1966; Sowers, 1979; Ringen and Daddow, 1990). Discharge from coal aquifers in the Wasatch and Fort Union Formations also may provide local recharge to alluvial aquifers where streams and rivers cross coal outcrops (Davis, 1976; Davis and Rechard, 1977; Brown, 1980; Stephenson, 1982; Martin and others, 1988).

Discharge from Quaternary alluvial and terrace-deposit aquifers occurs naturally by evapotranspiration, gaining streams, seeps, springs, and underflow, and anthropogenically by withdrawals from groundwater wells (Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Sowers, 1979; Stephenson, 1982; Rankl and Lowry, 1990; Ringen and Daddow, 1990). Evapotranspiration from Quaternary alluvial aquifers is likely to be highest in areas where the water table is near the land surface (Whitcomb and others, 1966). The direction of groundwater flow in most Quaternary alluvial aquifers generally is toward streams or in the direction of streamflow, including as underflow parallel to streamflow (Whitcomb and Morris, 1964; Goodwin and Hasfurther, 1982; Ringen and Daddow, 1990). Underflow moving through the Quaternary alluvium of the Belle Fourche River Valley at the South Dakota state line was estimated by Whitcomb and Morris (1964) to be less than 5 gallons per day.

Unconsolidated dune sand (eolian) deposits of Quaternary age (Quaternary dune sand deposits) consist of windblown silt and very fine- to medium-grained sand in active and inactive dunes (Denson and Horn, 1975, sheet 2). Most of the deposits are located in the PRSB, north of Casper in Natrona County and extending westward into the Casper arch/eastern WRSB area in western Converse County (plate 1). Quaternary dune sand deposits in these areas typically are less than 50-ft thick (Crist and Lowry, 1972; Hodson and others, 1973, sheet 3), but may be as much as 200-ft thick (Denson and Horn, 1975, sheet 2). Locally, Quaternary dune sand deposits may contain shallow unconfined groundwater in quantities sufficient for use, but well yields are small in many areas because sediment size is predominantly fine-grained and saturated thickness is small (Crist and Lowry, 1972; Hodson and others, 1973, sheet 3). Dune sand deposits are used as a source of water for domestic, livestock, and limited public-supply use in the unincorporated community of Powder River in western Converse County (Banner Associates, Inc., 2002). Groundwater in the dune sand deposits likely is perched at many locations, especially where the permeable dune sand deposits overlie weathered low-permeability, fine-grained mudrocks that typically compose a substantial percentage of underlying Tertiary- and Cretaceous-age rocks (Crist and Lowry, 1972). Hodson and others (1973) speculated that the deposits locally may provide recharge to underlying aquifers. Groundwater in the dune sand deposits in Natrona County discharges along the edges of the dunes (Crist and Lowry, 1972). Groundwater quality in the dune sand deposits is speculated to be better where saturated thickness is greatest and poorest in "areas of small saturated thickness where the water table is influenced more by contact with underlying Cretaceous shale" (Crist and Lowry, 1972, p. 81). Two well-yield measurements and groundwater-quality samples from dune sand deposits were inventoried in this study (plate 3; appendix E-1).

Unconsolidated landslide deposits of Quaternary age (Quaternary landslide deposits) consist of erosional rock debris transported by gravity to the base of steep slopes in the NERB study area. Because of topography, small seeps and springs may be found near the base of landslide deposits; however, the deposits rarely contain aquifers (Crist and Lowry, 1972; Hodson and others, 1973, sheet 3; Lowry and others, 1986; Camp Creek Engineering, Inc., 2010). The hummocky topography of the deposits likely helps trap precipitation and allow for recharge (Crist and Lowry, 1972; Camp Creek Engineering, Inc., 2010). One spring discharge measurement and one groundwater-quality sample from landslide deposits were inventoried in this study (plate 3; appendix E-1).

Unconsolidated glacial deposits of Quaternary age (Quaternary glacial deposits) consist of till and outwash deposits present in the Bighorn Mountains (plate 1). Whitcomb and others (1966) reported that glacial deposits in moraines in the Bighorn Mountains within Johnson County yielded water to numerous springs and seeps, but noted the areas where these deposits are found are located far from populated areas. Hodson and others (1973) noted that the groundwater potential of Quaternary glacial deposits was not well known. The investigators speculated that where saturated and permeable, glacial deposits likely would provide "good" quality groundwater. Furthermore, they speculated that yields for most groundwater wells completed in the deposits would be less than 50 gallons per minute (gal/min). No groundwater wells completed in Quaternary glacial deposits were inventoried as part of this study. One discharge measurement and one environmental groundwater-quality sample were inventoried for one spring issuing from Quaternary glacial deposits in the study area (plate 3; appendix E–1).

Chemical characteristics

The chemical characteristics of groundwater from saturated Quaternary unconsolidated deposits in the NERB study area (Quaternary alluvial aquifers, terrace-deposit aquifers, dune-sand (eolian) deposits, landslide deposits, and glacial deposits) are described in this section of the report. Groundwater quality of saturated Quaternary unconsolidated deposits in the NERB study area 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 groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix E–1).

7.2.1.1 Quaternary alluvial aquifers

The chemical composition of groundwater from Quaternary alluvial aquifers in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 71wells. Summary statistics calculated for available constituents are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram A). TDS concentrations indicated that waters were fresh (27 of 65 samples, concentrations less than or equal to 999 mg/L) to moderately saline (12 of 65 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–1; appendix I–1, diagram A). TDS concentrations ranged from 106 to 4,880 mg/L, with a median of 1,140 mg/L.

Several characteristics and constituents were measured in environmental water samples from Quaternary alluvial aquifers at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of constituents measured in environmental water samples at concentrations that exceeded health-based standards include: radon (all 9 samples exceeded the proposed USEPA MCL of 300 pCi/L, but none exceeded the AMCL of 4,000 pCi/L), strontium (3 of 25 samples exceeded the USEPA HAL of 4,000 µg/L), beryllium (2 of 27 samples exceeded the USEPA MCL of 4 µg/L), nitrate plus nitrite (3 of 52 samples exceeded the MCL of 10 mg/L), uranium (1 of 20 samples exceeded the USEPA MCL of 30 µg/L), and nitrate (3 of 71 samples exceeded the MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (54 of 65 samples exceeded the SMCL of 500 mg/L), sulfate (44 of 65 samples exceeded the SMCL of 250 mg/L), manganese (13 of 30 samples exceeded the SMCL of 50 µg/L), iron (3 of 30 samples exceeded the SMCL of 300 µg/L), chloride (2 of 64 samples exceeded the SMCL of 250 mg/L), and pH (1 of 65 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards for agricultural and livestock use. Characteristics and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (46 of 65 samples exceeded the WDEQ Class II standard of 200 mg/L), TDS (18 of 65 samples exceeded WDEQ Class II standard of 2,000 mg/L), manganese (7 of 30 samples exceeded WDEQ Class II standard of 200 µg/L), chloride (12 of 64 samples exceeded WDEQ Class II standard of 100 mg/L), SAR (9 of 65 samples exceeded WDEQ Class II standard of 8), selenium (1 of 32 samples exceeded WDEQ Class II standard of 20 µg/L), and boron (1 of 56 samples exceeded WDEQ Class II standard of 750 µg/L). One characteristic had values outside the range for livestock-use standards: pH (1 of 65 samples above upper WDEQ Class III limit of 8.5).

7.2.1.2 Quaternary terrace-deposit aquifers

The chemical composition of groundwater from Quaternary terrace-deposit aquifers in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram B). TDS concentrations measured in water from both wells (536 and 861 mg/L) indicate that the waters are fresh (TDS concentrations less than or equal to 999 mg/L) (appendix E–1; appendix I–1, diagram B).

Several characteristics and constituents were measured in environmental water samples from Quaternary terrace-deposit aquifers at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (radon) was measured in one well at a concentration greater than USEPA health-based standards (the one sample exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the AMCL of 4,000 pCi/L). Concentrations of one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use: TDS (both samples exceeded the SMCL of 500 mg/L) and sulfate (one sample exceeded the SMCL of 250 mg/L).

One constituent (sulfate) was measured in an environmental water sample from one well completed in a Quaternary terrace-deposit aquifer at a concentration greater than the agricultural-use standard (WDEQ Class II standard of 200 mg/L). No characteristics or constituents were measured at concentrations that exceeded applicable State of Wyoming livestock water-quality standards.

7.2.1.3 Quaternary dune sand (eolian) deposits

The chemical composition of groundwater from Quaternary dune sand (eolian) deposits in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram C). TDS concentrations measured in water from both wells (1,340 and 2,110 mg/L) indicate that the waters are slightly saline (concentrations between 1,000 to 2,999 mg/L) (appendix E–1; appendix I–1, diagram C).

Several characteristics and constituents were measured in environmental water samples from wells completed in the Quaternary dune sand (eolian) deposits at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards, but one characteristic and one constituent exceeded USEPA aesthetic standards for domestic use in both samples: TDS (SMCL of 500 mg/L) and sulfate (SMCL of 250 mg/L).

Concentrations of some characteristics and constituents in water from wells completed in the aquifers in Quaternary dune sand (eolian) deposits exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Two characteristics and constituents in environmental water samples from wells were measured at concentrations greater than agricultural-use standards: sulfate (both samples exceeded WDEQ Class II standard of 200 mg/L), SAR (one sample exceeded WDEQ Class II standard of 8), TDS (one sample exceeded WDEQ Class II standard of 2,000 mg/L), and chloride (one sample exceeded WDEQ Class II standard of 100 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

7.2.1.4 Quaternary landslide deposits

The chemical composition of groundwater from Quaternary landslide deposits in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram D). The TDS concentration measured in the sample collected from the spring (124 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (appendix E–1; appendix I–1, diagram D). On the basis of the characteristics and constituents analyzed, the quality of water from the spring issuing from Quaternary landslide deposits in the NERB study area was suitable for most uses. No characteristics or constituents exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.1.5 Quaternary glacial deposits

The chemical composition of groundwater from Quaternary glacial deposits in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram E). The TDS concentration from the spring (82 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (appendix E–1; appendix I–1, diagram E). On the basis of the characteristics and constituents analyzed, the quality of water from the one spring issuing from Quaternary glacial deposits in the NERB study area was suitable for all uses. No characteristics or constituents exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.2 Tertiary hydrogeologic units

The physical and chemical characteristics of Tertiary-age hydrogeologic units are described in this section of the report. Stock, domestic, and public-supply wells are completed in these units in the NERB. Tertiary hydrogeologic units are composed of lithostratigraphic units ranging from Pliocene to Paleocene in age (Plates 1, 2; figures 7-2, 7-8).

7.2.2.1 Tertiary intrusive igneous rocks

The physical and chemical characteristics of Tertiary intrusive rocks in the NERB study area are described in this section of the report.

Physical characteristics

Tertiary intrusive (plutonic) igneous rocks are found in the central "core" of the Black Hills uplift, and geographic extent is small in Wyoming (plate 1). These rocks generally are relatively impermeable, although Strobel and others (1999) noted that the hydrogeologic characteristics of these rocks in the South Dakota part of the Black Hills uplift varied with the amount of locally occurring fractures. Perched groundwater can be associated with intrusive sills in the Black Hills in South Dakota (Carter and others, 2002). One well completed in Tertiary intrusive igneous rocks was inventoried as this part of this study, indicating that these rocks locally can be sufficiently water-saturated and permeable to produce water to groundwater wells.

Chemical characteristics

The chemical composition of groundwater from Tertiary intrusive rocks in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram F). The TDS concentration from the well (80 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (appendix E–1; appendix I–1, diagram F). On the basis of the characteristics and constituents analyzed, the quality of water from the one well in Tertiary intrusive rocks in the NERB study area was suitable for most uses. No characteristics or constituents exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.2.2 Undifferentiated upper Miocene, lower Miocene, and Oligocene rocks

Undifferentiated Miocene and Oligocene rocks were mapped by Love and Christiansen (1985) as isolated outcrops or buttes with very small geographic extent in the Black Hills uplift (plate 1). The Miocene rocks likely include the Ogallala Formation and equivalent rocks, and the Oligocene-age rocks likely include the White River Group or Formation (Staatz, 1983; DeWitt and others, 1986; Love and others, 1993). No data were located describing the physical or chemical hydrogeologic characteristics of these rocks in the NERB study area in Wyoming.

7.2.2.3 Arikaree aquifer

The physical and chemical characteristics of the Arikaree aquifer in the NERB study area are described in this section of the report.

Physical characteristics

The Arikaree aquifer, composed of the water-saturated and permeable parts of the Arikaree Formation (Bartos and others, 2014, and references therein), is present in the vicinity of the Hartville uplift in the NERB study area (fig. 7-1; plates 1, 2). In the Hartville uplift and adjacent area and continuing southward outside the study area, the Arikaree aquifer is one of three Tertiary-age aquifers that may compose the regionally extensive High Plains aquifer system in Wyoming; the southeastern part of the NERB study area is the northernmost part of the High Plains aquifer system in Wyoming (see detailed description of High Plains aquifer system in Wyoming in Bartos and others, 2013, 2014). In the Wyoming Water Framework Plan, the Arikaree Formation in the NERB study area is classified as a major aquifer (WWC Engineering and others, 2007, fig. 4-9). The Arikaree aquifer in the NERB study area is used most commonly as a source of water for domestic, livestock and irrigation use, but the aquifer also is used as a source of public supply for the communities of Lusk and Manville (Western Water Consultants, Inc., 1997; HKM Engineering, Inc., and others 2002b; Hinckley Consulting, 2009).

The Arikaree Formation consists primarily of poorly to moderately cemented volcaniclastic, calcareous, very fine- to fine-grained sandstone interbedded with lenses of siltstone, limestone, and volcanic ash (Minick, 1951; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959, 1963; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Sato and Denson, 1967; Denson and Chisholm, 1971; Stanley, 1976; Swinehart and others, 1985). A basal conglomerate is present throughout much of the formation's geographic extent in the Hartville uplift area (Whitcomb, 1965; Western Water Consultants, Inc., 1997; Hinckley Consulting, 2009). Concretionary zones found in parts of the formation locally enhance permeability (Whitcomb, 1965). In Niobrara County where most of the Arikaree Formation is found in the NERB study area, thickness is highly variable and depends on the relief of the erosional surface that existed prior to formation deposition (Whitcomb, 1965; Hinckley Consulting, 2009). Whitcomb (1965) reported a maximum thickness of 600 ft or more in Niobrara County (Whitcomb, 1965, table 3). Hinckley Consulting (2009) reported a thickness of as much as 980 ft in the Lusk area.

Because of predominantly fine-grained sediment size in the Arikaree Formation, well yields in the Arikaree aquifer generally are small to moderate at most locations; consequently, large well yields sufficient for public supply or irrigation use are obtained by locating zones with coarse grain size and permeable concretionary sediments, and by penetrating large thicknesses of the aquifer (Rapp and others, 1957; Morris and Babcock, 1960; Weeks, 1964; Whitcomb, 1965; Western Water Consultants, Inc., 1997). Arikaree aquifer properties are highly variable due in part to differences in the type of permeability present. In most areas, Arikaree aquifer permeability is primary (intergranular). Areas of high permeability/transmissivity and associated large well yields reported in some studies are attributed to concretionary zones or secondary permeability development from localized fractures (Rapp and others, 1957; Morris and Babcock, 1960; Whitcomb, 1965; Western Water Consultants, Inc., 1997). Groundwater in the Arikaree aquifer generally is unconfined in the Lusk and Manville areas (Whitcomb, 1965; Crist, 1977; Western Water Consultants, Inc., 1997; Hinckley Consulting, 2009). Hydrogeologic data describing the Arikaree aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Arikaree aquifer in the NERB study area are described in this section of the report. Groundwater quality of the Arikaree aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix E–1).

The chemical composition of water from the Arikaree aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 57 wells. Summary statistics calculated for available constituents are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram G). TDS concentrations indicated that waters were fresh (55 of 56 samples, concentrations less than or equal to 999 mg/L) to slightly saline (1 of 56 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix E–1; appendix I–1, diagram G). TDS concentrations ranged from 198 to 1,150 mg/L, with a median of 285 mg/L.

Concentrations of some characteristics and constituents in water from the Arikaree aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents measured in environmental water samples at concentrations that exceeded health-based standards include: radon (all 4 samples exceeded the proposed USEPA MCL of 300 pCi/L, but none exceeded the AMCL of 4,000 pCi/L), gross-alpha radioactivity (8 of 11 samples exceeded the USEPA MCL of 15 pCi/L), uranium (2 of 5 samples exceeded the USEPA MCL of 30 mg/L), nitrate (4 of 31 samples exceeded the MCL of 10 mg/L), and nitrate plus nitrite (1 of 17 samples exceeded the MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (6 of 56 samples exceeded the SMCL of 500 mg/L), pH (1 of 52 samples above upper SMCL limit of 8.5), and sulfate (1 of 57 samples exceeded the SMCL of 250 mg/L).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards were gross-alpha radioactivity (8 of 11 samples exceeded WDEQ Class II standard of 15 pCi/L), chloride (1 of 57 samples exceeded WDEQ Class II standard of 100 mg/L), and sulfate (1 of 57 samples exceeded the WDEQ Class II standard of 200 mg/L). One characteristic and one constituent had values outside the range for livestock-use standards: gross-alpha radioactivity (8 of 11 samples exceeded WDEQ Class III standard of 15 pCi/L) and pH (1 of 52 samples above upper WDEQ Class III limit of 8.5).

7.2.2.4 White River hydrogeologic unit

The physical and chemical characteristics of the White River hydrogeologic unit in the NERB study area are described in this section of the report.

Physical characteristics

Within the NERB study area, the White River Group or Formation is present in the Hartville uplift area, PRSB, and Black Hills uplift area (plate 1). The White River Group or Formation is present throughout the Hartville uplift area, although the entire areal extent generally cannot be seen on geologic maps showing outcrops (plate 1) because of burial by the overlying Arikaree Formation. The White River Group or Formation in the PRSB and Black Hills uplift area occurs as isolated outcrops or buttes with very limited geographic extent (plate 1).

The White River Group or Formation consists primarily of massive, argillaceous (clayey), calcareous, poorly to moderately cemented mudrocks (commonly siltstone) interbedded with minor amounts of locally occurring poorly to moderately cemented sandstone, conglomerate, and volcanic ash beds throughout its geographic extent (Minick, 1951; Rapp, 1953; Rapp and others, 1953, 1957; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959, 1963; Denson and Bergendahl, 1961; Whitcomb, 1965; Lowry and Crist, 1967; Sato and Denson, 1967; Denson and Chisholm, 1971; Stanley, 1976; Singler and Picard, 1979a,b; Cassiliano, 1980; Swinehart and others, 1985). At many locations, the “White River” is divided into an upper part (Brule Formation or Member) and a lower part (Chadron Formation or Member). In Niobrara County where most of the White River Group or Formation is found in the NERB study area, maximum thickness is 500 ft or more (Whitcomb, 1965, table 3). Whitcomb and Morris (1964) reported White River Formation thickness was 150 ft or more in the Black Hills uplift in Crook County, but that very limited areal extent prevented any potential for water-supply development.

Permeability of the White River Formation or Group in the vicinity of the Hartville uplift is highly variable, and thus, the lithostratigraphic unit or parts of the unit are classified as either an aquifer where sufficiently water-saturated and permeable to produce economic quantities of water (White River aquifer) or as a confining unit where impermeable (White River confining unit) (Bartos and others, 2014, and references therein). Because of this highly variable permeability, the Wyoming Water Framework Plan (WWC Engineering and others, 2007) classified the White River Group or Formation as a marginal aquifer in areas with low to moderate well yields, and a major aquifer in areas with locally high well yields.

In the vicinity of the Hartville uplift and continuing southward beyond the NERB study area boundary, the White River hydrogeologic unit, where an aquifer, is one of three Tertiary-age aquifers (Ogallala, Arikaree, and White River aquifers; Ogallala aquifer located south of the NERB study area boundary) that may compose the regionally extensive High Plains aquifer system in Wyoming (Bartos and others, 2013, 2014). The southeastern part of the NERB study area coincides with the northernmost part of the High Plains aquifer system in Wyoming (fig. 7-1). However, in contrast to the Arikaree aquifer, the White River hydrogeologic unit is not considered part of the High Plains aquifer system throughout the area where the areal extent of the hydrogeologic unit and aquifer system coincide. The White River hydrogeologic unit is considered part of the aquifer system primarily in areas where the overlying Ogallala and (or) Arikaree aquifers were removed by erosion and the unit is exposed at land surface or subcrops below Quaternary-age unconsolidated deposits (alluvium and terrace deposits). In these areas, and where the upper part of the hydrogeologic unit is water-saturated and permeable (and thus, an aquifer), the White River hydrogeologic unit (White River aquifer) typically is the principal aquifer of the High Plains aquifer system. More deeply buried water-saturated and permeable parts of the White River hydrogeologic unit generally are not considered part of the High Plains aquifer system because hydraulic connection with shallower parts of the unit typically is limited due to intervening low-permeability strata (typically mudrocks) that compose most of the White River Group or Formation. Locally, the White River aquifer may be hydraulically connected with overlying water-saturated Quaternary unconsolidated deposits. The White River aquifer also may be considered part of the High Plains aquifer system in areas where hydraulically connected to the overlying/adjacent Arikaree and (or) Ogallala aquifers. Where impermeable and not hydraulically connected to the Arikaree and (or) Ogallala aquifers, the White River hydrogeologic unit acts as a confining unit to the overlying High Plains aquifer system.

Studies completed south and southeast of the NERB study area indicate permeability in the White River Group or Formation is attributable to either the presence of primary permeability in locally occurring coarse-grained deposits such as sandstone lenses and stringers and occasional conglomerates, or more commonly, secondary permeability in various mudrocks (claystone, mudstone, siltstone) that compose most of the unit(s). Consolidated mudrocks such as siltstone that compose most of the White River Group or Formation have minimal primary porosity and permeability and generally yield no water or small volumes of water to groundwater wells. Yields to groundwater wells completed in mudrocks sufficient for use generally are obtained only in zones with secondary porosity and permeability development. Numerous studies in southeastern Wyoming attribute the zones with secondary permeability to fractures, joints, piping, and fissures (Knight and Morgan, 1937; Dockery, 1940; Warner, 1947; Babcock and Rapp, 1952; Rapp, 1953; Rapp and others, 1953, 1957; Babcock and Bjorklund, 1956; Bjorklund, 1959; Morris and Babcock, 1960; Whitcomb, 1965; Lowry, 1966; Lowry and Crist, 1967). Within the NERB study area in Niobrara County, Stock (1981) noted permeability in the White River Formation near the Old Woman anticline was both primary and secondary, but that secondary permeability attributable to fractures was dominant.

The White River hydrogeologic unit is rarely developed as a source of water supply in the Hartville uplift area. The overlying Arikaree aquifer provides water of sufficient quantity and quality for most intended purposes in this area, and the predominantly fine-grained nature of the sediments composing the White River hydrogeologic unit has deterred local exploration of developmental possibilities (Bradley, 1956; Hinckley Consulting, 2009).

Hydrogeologic data describing the White River hydrogeologic unit where locally an aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3. Yields of groundwater wells completed in locally occurring coarse-grained zones of the formation (sand- and gravel-sized particles in channel deposits) and in areas with mudrocks with minor secondary permeability development generally are small to moderate. Large well yields sufficient for irrigation or public-supply development can be obtained only in areas where the formation has locally extensive secondary porosity and permeability development, as exemplified in areas south of the NERB study area (for example, Lowry, 1966; Lowry and Crist, 1967; Crist and Borchert, 1972; Bartos and others, 2014).

Chemical characteristics

The chemical characteristics of groundwater from the White River hydrogeologic unit where locally an aquifer in the NERB study area are described in this section of the report.

Groundwater quality of the White River aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix E–1).

The chemical composition of water from the White River aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 5 wells. Summary statistics calculated for available constituents are listed in appendix E–1. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram H). TDS concentrations indicated that waters were fresh (concentrations less than or equal to 999 mg/L) (appendix E–1; appendix I–1, diagram H). TDS concentrations ranged from 320 to 495 mg/L, with a median of 428 mg/L.

Concentrations of some characteristics and constituents in water from the White River aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent (fluoride) exceeded health-based and aesthetic standards (1 of 5 samples exceeded the USEPA MCL of 4 mg/L and the SMCL of 2 mg/L). One characteristic (SAR) exceeded State of Wyoming standards for agricultural use (3 of 5 samples exceeded WDEQ Class II standard of 8). No characteristics or constituents were measured at concentrations that exceeded applicable State of Wyoming livestock water-quality standards.

7.2.2.5 Wind River aquifer (Wind River structural basin)

The physical and chemical characteristics of the Wind River aquifer for the small part of the Wind River structural basin (WRSB) within the NERB study area are described in this section of the report.

Physical characteristics

Present in the part of the WRSB within the NERB study area (plates 1, 2), the Wind River aquifer consists of water-saturated and permeable sandstone beds in the Eocene-age Wind River Formation (Bartos and others, 2012, and references therein). In the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9), the Wind River Formation was classified as a major aquifer. The Wind River Formation is composed of an interbedded sequence of fluvially deposited claystone, shale, siltstone, and conglomerate, with lenticular beds of fine- to coarse-grained sandstone of variable thickness and areal extent; small amounts of bentonite, tuff, and limestone also may be present (Morris and others, 1959; McGreevy and others, 1969; Richter, 1981). Thickness of the Wind River Formation in the WRSB ranges from about 100 ft along mountain flanks to about 5,000 ft in the central part of the basin (Bartos and others, 2012). Coarser-grained deposits may be more abundant along the basin margins because of proximity to sediment sources such as the Wind River Mountains (Whitcomb and Lowry, 1968).

In the WRSB, the Wind River aquifer is underlain by the Indian Meadows confining unit or by the Fort Union aquifer, in the absence of the Eocene-age Indian Meadows Formation (Bartos and others, 2012, plate II). In the Wind River Mountains, the Wind River Formation may be underlain by the Conglomerate of Roaring Fork. Where buried, the aquifer is overlain by the Aycross-Wagon Bed confining unit (composed of the volcaniclastic Eocene-age Tepee Trail and Aycross Formations or siliciclastic Wagon Bed Formation) or Quaternary unconsolidated deposits (Bartos and others, 2012, plate II).

The Wind River aquifer is used as a source of water for domestic, livestock, irrigation, industrial, and public-supply purposes throughout the WRSB (Taucher and others, 2012). Many groundwater wells are installed in the Wind River aquifer in the WRSB because it is present at or near land surface (crops out) throughout most of the basin. The population is very sparse for the part of the aquifer that is within the study area, so aquifer use in the NERB study area is minimal and primarily for livestock purposes. Regardless of location in the WRSB, most groundwater wells completed in the Wind River aquifer are for livestock and domestic use because of relatively low well yields throughout much of the aquifer extent and water quality that may preclude some uses without treatment (Morris and others, 1959; Whitcomb and Lowry, 1968; McGreevy and others, 1969; Richter, 1981; Bartos and others, 2012). Groundwater in the Wind River aquifer is mostly under confined conditions, but unconfined (water-table) conditions are likely at shallow depths where the Wind River Formation outcrops (Whitcomb and Lowry, 1968; McGreevy and others, 1969; Richter, 1981). Hydrogeologic data describing the Wind River aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Wind River aquifer in the WRSB are described in this section of the report. Groundwater quality of the Wind River aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix H).

The chemical composition of water from the Wind River aquifer was characterized and the quality evaluated on the basis of as many as four produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram A). TDS concentrations from produced-water samples indicated that the waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L) (appendix H; appendix L, diagram A). TDS concentrations in produced-water samples from the Wind River aquifer ranged from 1,117 to 2,603 mg/L, with a median of 1,638 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Several characteristics and constituents were measured in produced-water samples at concentrations greater than aesthetic standards for domestic use: TDS (all 4 samples exceeded SMCL limit of 500 mg/L), pH (2 of 4 samples above upper SMCL limit of 8.5), chloride (2 of 4 samples exceeded SMCL limit of 250 mg/L), and sulfate (1 of 4 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water water samples from the Wind River aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 4 samples exceeded WDEQ Class II standard of 8), chloride (all 4 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (2 of 4 samples exceeded WDEQ Class II standard of 200 mg/L), and TDS (1 of 4 samples exceeded WDEQ Class II standard of 2,000 mg/L). One characteristic (pH) was measured at a value that exceeded a livestock-use standard (2 of 4 samples above upper WDEQ Class III limit of 8.5).

7.2.2.6 Lower Tertiary aquifer system (Wasatch and Fort Union Formations in the Powder River structural basin)

Hydrogeologic units composing the lower Tertiary aquifer system in the PRSB within the NERB study area are identified and described in this section of the report. The term "lower Tertiary" is not a formally-recognized stratigraphic name, therefore, "lower" will not be capitalized when discussing this aquifer system.

Physical characteristics

The areally extensive lower Tertiary aquifer system coincides closely with the boundary of the PRSB in Wyoming and Montana and includes a large part of the NERB study area (fig. 7-7; plate 2). The regional aquifer system consists of the Wasatch Formation and the members of the Fort Union Formation grouped into different hydrogeologic units, generally named after their respective lithostratigraphic units (figs. 7-2, 7-7; plate 2).

The Eocene-age Wasatch Formation is exposed at the surface throughout much of the PRSB in Wyoming (plate 1). The Wasatch Formation conformably overlies the Paleocene-age Fort Union Formation in the center of the basin and unconformably overlies it along the basin margins (Seeland, 1992). Although the Wasatch Formation is considered to overlie the Fort Union Formation conformably or unconformably over most of the basin, at many locations lithologies of the two formations are so similar that no distinction between the formations can be made except by detailed mineralogical or palynological studies (Tschudy, 1976; Denson and others, 1989a, b; Nichols, 1994, 1998; Nichols and Brown, 1992; Ellis and others, 1999a, b, c). Furthermore, the contact between the two formations and its relation to the Paleocene-Eocene boundary remains controversial (Flores, 1999; Flores and Bader, 1999). Thickness of the lower Tertiary aquifer system in the PRSB of Wyoming and Montana is as much as 7,180 ft, and volume is an estimated 1,381 trillion cubic ft (ft^3) (Thamke and others, 2014, table 5).

The Wasatch Formation consists primarily of nonmarine fluvial and paludal (swamp and marsh) sediments composed of fine- to coarse-grained, lenticular, discontinuous sandstone beds interbedded with fine-grained interfluvial/overbank mudrocks such as shale, siltstone, claystone, and mudstone (Lewis and Hotchkiss, 1981; Seeland, 1992). In the northwestern part of the PRSB along the Bighorn Mountains, the Wasatch Formation contains two local conglomeratic facies (Kingsbury Conglomerate and Moncrief Members; plate 1) that were deposited in alluvial fans; both members grade into the finer-grained facies composing most of the Wasatch Formation within a few miles east of the Bighorn Mountains (Hose, 1955; Lowry and Cummings, 1966; Seeland, 1992). The Wasatch Formation also contains many subbituminous coal beds that were deposited in extensive, long-lived, low-lying swamps, with the thickest beds in the western and central parts of the PRSB, especially near Lake De Smet where the thickest coal bed in the United States locally can exceed more than 200 ft (Mapel, 1959; Glass, 1980; Luppens and others, 2015, and references therein). Economic deposits of uranium ores in the form of uraninite formed as roll-front deposits in sandstones also are contained in the formation; the deposits have been mined for decades, primarily in the central to southern part of the PRSB (Sharp and Gibbons, 1964; Sharp and others, 1964; Hagmaier, 1971; Dahl and Hagmaier, 1974, 1976; Santos, 1981; Lowry and others, 1993).

Maximum thickness of the Wasatch Formation is about 3,000 ft along the basin axis located about 5 miles (mi) southeast of Buffalo, Wyoming (Seeland, 1992). Fine-grained rocks (primarily mudrocks consisting of overbank floodplain deposits) may compose as much as two-thirds of Wasatch Formation thickness, although mapping of the percentage of total sandstone in the formation indicates that sandstone can compose 50 percent or more of total formation thickness in some parts of the PRSB (Seeland, 1992, fig. 10).

The Fort Union Formation is exposed primarily along the margins of the PRSB in Wyoming where the overlying Wasatch Formation is absent (plate 1). Like the Wasatch Formation, rocks composing the Fort Union Formation were deposited primarily in fluvial and paludal environments (Brown, 1993, and references therein). Along the central to eastern part of the PRSB, the Fort Union Formation is nearly flat and dips about 2 to 3 degrees to the west towards the basin axis, whereas west of the basin axis, the formation dips from 10 to 25 degrees to the east (Glass, 1997).

The Fort Union Formation is divided into three members—from stratigraphically youngest to oldest, the Tongue River Member, Lebo Shale Member (also known as Lebo Member), and Tullock Member (fig. 7-2; Dobbin and Horn, 1949). Because of lateral facies or contact relationships, the three members of the Fort Union Formation are difficult to distinguish from one another in some parts of the PRSB, especially in the subsurface (Brown, 1993). The Tongue River Member is as much as 1,860-ft thick and consists primarily of lenticular, discontinuous, fine- to medium-grained sandstone beds interbedded with fine-grained rocks such as siltstone, claystone, mudstone, shale/carbonaceous shale, thin to thick subbituminous coal beds, and sparse limestone

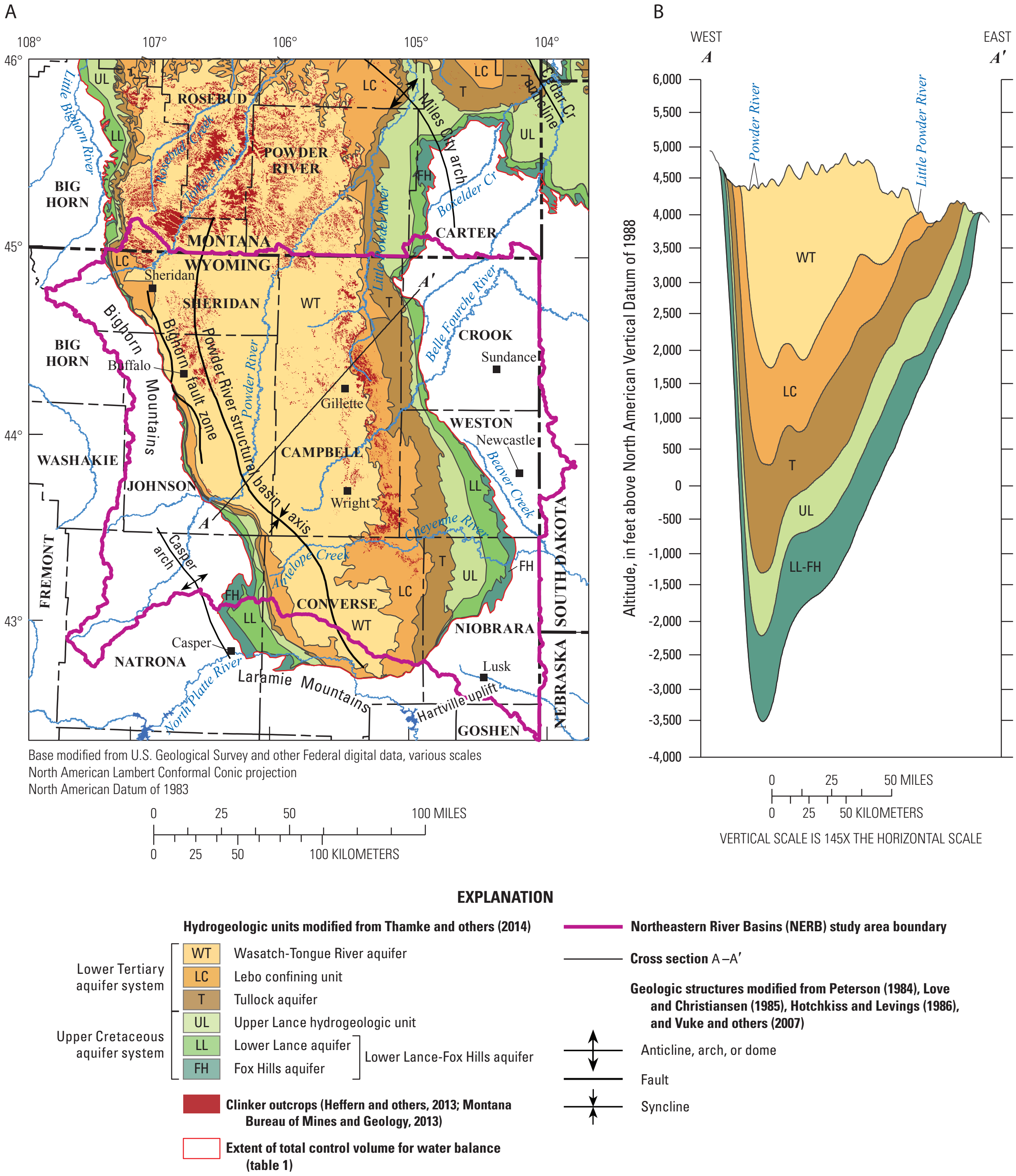


Figure 7-7. A, Outcrops of hydrogeologic units and B, cross section of the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana (modified from Thamke and others, 2014; and Long and others, 2014).

(Lewis and Hotchkiss, 1981; Flores and others, 1999, and references therein). Coal beds in the Tongue River Member generally are more common, thicker, and laterally extensive than in the overlying Wasatch Formation. Most coal mined and coalbed natural gas produced in the PRSB comes from the thick coal beds in the Tongue River Member (Ellis, 1999; Ellis and others, 1999a, b, c; Luppens and others, 2015). The Lebo Shale Member conformably underlies the Tongue River Member and is 3,000-ft thick or more in the PRSB; the member consists primarily of shale or mudstone interbedded with lesser amounts of sandstone, siltstone, and sparse, very thin coal beds (Law, 1975; Lewis and Hotchkiss, 1981). Differentiating the Tongue River Member from the Lebo Shale Member is difficult in some parts of the PRSB, especially where the Lebo Shale Member has substantial sandstone content or the Tongue River Member has substantial shale/mudstone content; consequently, the two units were mapped together on many geologic maps. In addition, the members of the Fort Union Formation identified on different geologic maps of the same area can differ because of alternate stratigraphic interpretations. The Tullock Member conformably underlies the Lebo Shale Member and overlies the Upper Cretaceous Lance Formation, and maximum thickness is as much as 1,440 ft (Brown, 1993) or 1,962 ft (Lewis and Hotchkiss, 1981). The Tullock Member consists primarily of lenticular, discontinuous, fine- to medium-grained sandstone beds interbedded with fine-grained rocks such as siltstone, claystone, mudstone, carbonaceous shale, rare limestone, and thin coal beds (Curry, 1971; Brown, 1993). The contact of the Tullock Member with the underlying Lance Formation is gradational and difficult to determine in places (Lowry, 1972, 1973; Brown, 1993, and references therein; Merewether, 1996).

Coal in the Fort Union Formation developed in low-lying peat swamps and raised mires along major basin-axis streams, and associated detrital rocks were deposited by trunk-tributary, meandering, anastomosed, and braided streams (Flores, 1986, 1999; Flores and others, 1999). Coal bed splits and pinch outs formed in areas where the peat was incised by fluvial channels (sandstone) or inundated with overbank, floodplain, or floodplain-lake deposits (mudrocks). The stratigraphic relations of coal beds within and between the Fort Union and Wasatch Formations are complex, as beds may merge, split, and pinch out within short distances. The nomenclature of individual coal beds and zones also varies across the basin in Wyoming and adjacent Montana. The thickest and most laterally continuous coal beds are associated with the Tongue River Member of the Fort Union Formation in a coal zone identified as the Wyodak-Anderson coal zone (Averitt, 1975; Glass, 1980, 1997; Flores and others, 1999; Jones and Rogers, 2007; Jones, 2008, 2010; Flores and others, 2010, and references therein; Jones and others, 2011; Luppens and others, 2015, and references therein). Most of the coal mined and coalbed natural gas (CBNG) produced to date (2017) in the PRSB has been obtained from the various coal beds in this coal zone. Unfortunately, nomenclature used to identify the various coal beds in the PRSB in Wyoming differs among studies, so many publications must be consulted to understand the different names applied to Wasatch and Fort Union Formation coals and coal zones.

In many parts of the PRSB, outcropping or subcropping Wasatch and Fort Union Formation coal beds have burned naturally and baked, welded, and melted rocks interbedded with and surrounding the beds to form deposits known as clinker (also locally referred to as scoria) (areal extent shown on fig. 7-7; Heffern and others, 1993, 2007, 2013; Heffern and Coates, 1997; Coates and Heffern, 1999). Burning of the coal beds reduces volume and fractures the surrounding baked, welded, and melted rocks; these rocks commonly collapse and fill in the void left by the burned coalbed, resulting in a zone with high porosity for water infiltration and storage as well as very high permeability (Heffern and Coates, 1999). Clinker is a distinct orange to red to purple color and covers as much as 378 mi^2 in the Wyoming part of the PRSB (Heffern and others, 2013). Clinker caps many topographically elevated areas because the deposits are resistant to erosion. At some locations, springs issue from the clinker where the water table intersects the land surface or where underlain by impermeable strata. Where permanently saturated, clinker contains productive local aquifers. In some cases, clinker aquifers extend some distance into the buried part of the associated coal bed(s).

Individual aquifers in the Wasatch and Fort Union Formations in the PRSB consist of sandstone beds and lenses, coal beds, and clinker where these lithologic units are water-saturated and sufficiently permeable to produce usable quantities of water (Littleton, 1950; Rapp, 1953; Morris, 1956; Dana, 1962; Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Hagmaier, 1971; Groundwater Subgroup, 1974; Hodson and others, 1973, sheet 3, and references therein; King, 1974; Feathers and others, 1981; Lewis and Hotchkiss, 1981; Bloyd and others, 1986; Crist, 1991; Fogg and others, 1991). Sandstone and coal aquifers in both the Wasatch and Fort Union Formations are used as sources of water throughout the PRSB, most commonly for livestock and domestic use; sandstone aquifers in the Fort Union Formation also are used locally for public-supply and industrial purposes where water of sufficient quantity and quality can be obtained for these uses (Feathers and others, 1981; Martin and others, 1988; Fogg and others, 1991; Wyoming State Engineer's Office, 1995; HKM Engineering, Inc., and others, 2002a, b; Wester-Wetstein and Associates, 2004a; Morrison-Maierle, Inc., 2007; HDR Engineering, Inc., 2009, 2012; Ogle and others, 2011).

Numerous municipal water systems located in the PRSB utilize groundwater from the Fort Union Formation as a source of water for public supply (HKM Engineering, Inc., and others, 2002a, b). Much of the water withdrawn from the Fort Union Formation for public-supply purposes is obtained and used in the vicinity of and used by the cities of Gillette and Wright and immediately outlying areas (Wyoming State Engineer's Office, 1995; HKM Engineering, Inc., and others, 2002a, b; Wester-Wetstein and Associates, 2004a; Brown and Caldwell, 2005, and references therein; Morrison-Maierle, Inc., 2007; HDR Engineering, Inc., 2009, 2012). These withdrawals have resulted in substantial groundwater declines in the Fort Union Formation in the vicinity of Gillette (for example, Wester-Wetstein and Associates, 2004a; Morrison-Maierle, Inc., 2007; Wyoming State Engineer's Office, 2012).

Hydraulic characteristics determined from wells completed in the sandstone and coal beds in both the Wasatch and Fort Union Formations, including well yields, are highly variable (plate 3), reflecting highly variable lithology and individual aquifer lateral and vertical extent. In addition, differences in well construction also likely contribute to large variability in reported hydraulic characteristics because wells commonly are open to multiple individual aquifers in the formations (for example, Wester-Wetstein and Associates, 2004a). Yields are low for most wells completed in both formations, as indicated by a median well yield of 7 gal/min for the Wasatch Formation and 10 gal/min for the Fort Union Formation for wells inventoried as part of this study (plate 3). Obtaining yields sufficient for industrial and public-supply use typically requires location of thick sandstone aquifers and penetration of multiple sandstone aquifers within a member of the Fort Union Formation or within multiple members of the Fort Union Formation, as exemplified by city of Gillette public-supply groundwater wells constructed to penetrate multiple thick sandstone beds in one or more members of the Fort Union Formation to maximize yield (Wester-Wetstein and Associates, 2004a; Brown and Caldwell, 2005, and references therein).

The sandstone beds and lenses containing aquifers in the Wasatch and Fort Union Formations ("sandstone aquifers") vary widely in geometry, but most are lenticular and laterally and vertically discontinuous (Littleton, 1950; Morris, 1956; Dana, 1962; Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Hagmaier, 1971; Groundwater Subgroup, 1974; Hodson and others, 1973, sheet 3, and references therein; King, 1974; Feathers and others, 1981; Lewis and Hotchkiss, 1981; Bloyd and others, 1986; Crist, 1991; Fogg and others, 1991; Wester-Wetstein and Associates, 2004a; Brown and Caldwell, 2005, and references therein; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; AECOM, Inc., 2009, 2014). Sandstone bed thickness varies widely as well, but most beds are thin relative to member or formation thickness. Areal extent of individual sandstone aquifers in the Wasatch and Fort Union Formations typically does not extend more than a few miles at most, but more laterally extensive sandstone aquifers are present in parts of the basin (for example, Hunter, 1999). Despite limited geographic extent, sandstone aquifers in both formations are used throughout much of the PRSB for domestic and stock use because both formations cover much of the basin and contain the only aquifers that can be developed at economical drilling depths; however, widely varying groundwater quality and presence of certain constituents such as fluoride at concentrations greater than MCLs without treatment or blending with other sources of water commonly limits many intended uses, including public supply (for example, Wester-Wetstein and Associates, 2004a). The available volume of groundwater from all sandstones in the Wasatch and Fort Union Formations has been estimated to be 6.19×1013 cubic feet (ft^3) (Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002) and 2.44×1013 ft^3 (Hinaman, 2005, table 5).

Sandstone beds containing aquifers commonly are surrounded (confined) by fine-grained, low-permeability rocks such as siltstone, mudstone, claystone, and shale/carbonaceous shale that form confining layers, locally resulting in a complicated system of discontinuous aquifers with varying groundwater levels (hydraulic heads) and different degrees of horizontal and vertical hydraulic connection/confinement. Unconfined conditions typically occur where the sandstones composing the aquifers are exposed at land surface (crop out) or where buried at shallow depths. Confined or semi-confined conditions predominate with increasing depth in both formations. Artesian pressure is sufficient in some areas to cause groundwater wells completed in confined aquifers to flow, most commonly along the major river valleys. Pore pressures in the sandstone aquifers (and coal aquifers) reportedly are below hydrostatic pressure (sub-hydrostatic; Ross and Zoback, 2008). Groundwater wells completed only in the fine-grained rocks yield insufficient quantities of water for the rocks to be considered aquifers, even though the rocks may be water-saturated and static water levels may be the same as in adjacent sandstone aquifers (Groundwater Subgroup, 1974; Brown, 1980; Martin and others, 1988). Groundwater levels measured in some wells completed in Wasatch and Fort Union Formation sandstone and coal aquifers are affected by naturally occurring gas (primarily methane) present in both formations throughout much of the PRSB (Whitcomb and others, 1966; Lowry and Rankl, 1987). The gas can contribute to hydraulic head and may cause water levels in groundwater wells to rise higher than if only artesian pressure was present.

Water-saturated and permeable coal beds in both the Wasatch and Fort Union Formations contain important aquifers in the PRSB. Coal beds in the Wyodak-Anderson coal zone and other thick coal beds in the Fort Union Formation compose some of the most geographically extensive and laterally continuous aquifer(s) in the lower Tertiary lithostratigraphic units throughout the PRSB in Wyoming and Montana (Stephenson, 1982; Slagle and others, 1985; Bloyd and others, 1986; Daddow, 1986; Martin and others, 1988; Fogg and others, 1991). The aquifer associated with the Wyodak-Anderson coal zone, known as the Wyodak coal aquifer or Wyodak-Anderson coal/coal bed aquifer, is the most important coal aquifer in the eastern and central PRSB because of thickness, wide geographic extent, and sufficient permeability and groundwater quality (fresh or slightly saline waters) for different uses, although most use is for stock watering (Stephenson, 1982; Bloyd and others, 1986; Daddow, 1986; Martin and others, 1988; Fogg and others, 1991; Murphy and Stockdale, 2000; Bartos and Ogle, 2002). The Wyodak-Anderson coal aquifer consists not only of the main Wyodak coal bed, but also the associated coal beds where the Wyodak coal bed split and separated into multiple beds, sandstone beds interbedded between the coal beds, and clinker beds associated with the coal beds along the coal outcrop (Bloyd and others, 1986; Daddow, 1986; Martin and others, 1988). Primary (matrix) permeability of PRSB coal beds is small to nonexistent, and most is secondary and attributable to naturally occurring fractures known as cleats (Stone and Snoeberger, 1977; Stoner, 1981; Rehm and others, 1980; Dobson, 1996; Weeks, 2005, and references therein). Groundwater flow in the Wyodak-Anderson coal aquifer is affected by differences in the distribution and density of coal fractures (cleats), and in places where the Wyodak coal bed separates to form two or more coal beds with interbedded claystone, shale, or sandstone (Martin and others, 1988).

The Wyodak-Anderson coal aquifer is unconfined near outcrops and becomes confined as the coal beds dip westward below the water table. The aquifer is confined from above by low-permeability fine-grained sedimentary rocks in the Wasatch Formation and Tongue River Member of the Fort Union Formation and below by low-permeability fine-grained sedimentary rocks in the Tongue River Member. The amount of hydraulic connection under natural conditions between the Wyodak-Anderson coal aquifer and underlying and overlying sandstone aquifers is unclear and likely differs by location because of spatially variable hydrogeologic characteristics. Some investigators have suggested that natural downward vertical flow or leakage from overlying sandstone aquifers to the Wyodak-Anderson coal aquifers may be small to nonexistent because of low vertical hydraulic conductivity of intervening fine-grained rocks (Davis and Rechard, 1977; Feathers and others, 1981; Bloyd and others, 1986), even though a downward vertical gradient between the coal aquifer and the overlying aquifers is present commonly in many areas (Groundwater Subgroup, 1974; Davis, 1976; Bureau of Land Management, 1999, 2003; Bartos and Ogle, 2002; Ross and Zoback, 2008). Some natural leakage/hydraulic connection likely occurs downward where the hydraulic gradient allows for downward vertical groundwater flow/leakage and where sandstone beds are in physical contact with the coal aquifer or are separated from the coal aquifer with minimal intervening strata (Bureau of Land Management, 1999, 2003; Bartos and Ogle, 2002; Applied Hydrology Associates, Inc., and Greystone Consultants, Inc., 2002; Ross and Zoback, 2008).

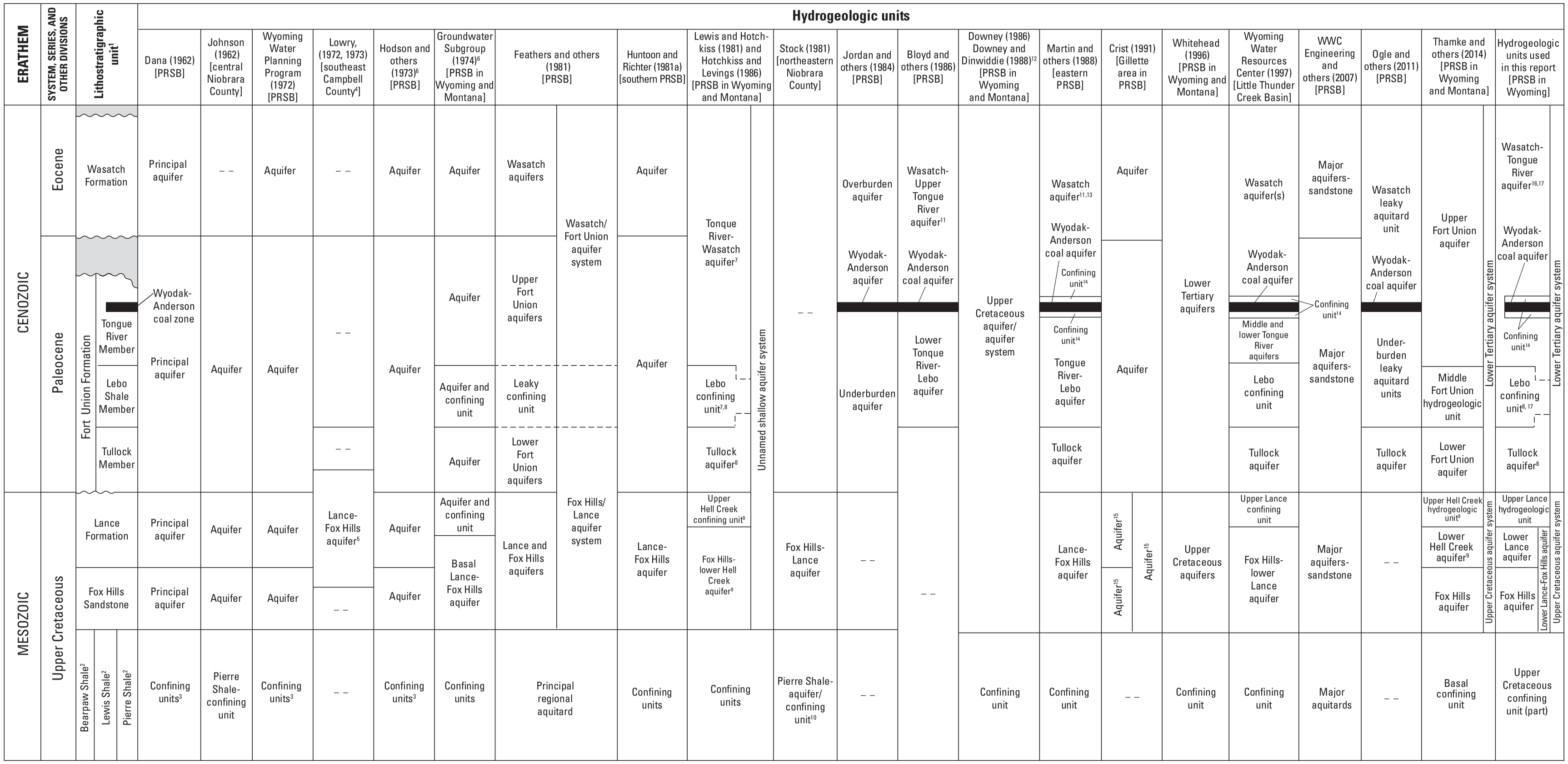
Induced leakage/hydraulic connection from some overlying sandstone aquifers in the Wasatch Formation and Tongue River Member of the Fort Union Formation to the Wyodak-Anderson coal aquifer has occurred in parts of the PRSB as a result of CBNG development (Ross and Zoback, 2008; Taboga and others, 2015, 2017, and references therein). Pumping of groundwater from the Wyodak-Anderson coal aquifer to reduce aquifer pressure and facilitate CBNG production has induced groundwater flow from sandstone aquifers to the coal aquifer, resulting in declines of groundwater levels (hydraulic head) measured in some underlying and overlying sandstone aquifers (Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; AECOM, Inc., 2009, 2014; Taboga and others, 2015, 2017, and references therein). Ross and Zoback (2008) examined pore pressure changes with time in numerous PRSB coal aquifers and overlying/underlying sandstone aquifers. The investigators found that after 8 to 13 years of groundwater-level monitoring, none of the sandstone aquifers separated by more than 200 ft of strata vertically from coal beds pumped to produce CBNG indicated hydraulic connection with the coal beds. CBNG production also has lowered groundwater levels in some of the coal beds composing the Wyodak-Anderson coal aquifer (AECOM, Inc., 2009, 2014; Taboga and others, 2015, 2017, and references therein). In addition, dewatering to facilitate coal mining also has contributed to substantial local groundwater-level declines in both the sandstone and coal aquifers in the eastern PRSB (AECOM, Inc., 2009, 2014).

Regional hydrostratigraphy

Regional hydrogeologic units composed of the Wasatch Formation and the three members of the Fort Union Formation have been variously defined and named (fig. 7-8). Variations in hydrostratigraphic nomenclature reflect different purposes and scales of study; different interpretations of the amount of local, intermediate, and regional flow in and between the individual aquifers within the lithostratigraphic units; and the interpreted amount of regional hydraulic connection between the different lithostratigraphic/hydrogeologic units.

Many studies examining the hydrogeology of the Wasatch and Fort Union Formations in the PRSB generally were local in nature and broadly identified the individual formations as aquifers named after their respective formation name (fig. 7-8; "Wasatch or Fort Union aquifers"), each consisting of a series of discontinuous lenticular sandstone and coal aquifers with varying hydraulic connection. Because of the discontinuous nature of these individual aquifers, definition of hydrogeologic units including aquifers composed of all or parts of both formations on a regional basis is difficult. Nevertheless, subsequent studies with a regional emphasis defined regional hydrogeologic units consisting of all or parts of both formations in the PRSB (fig. 7-8); many of these studies were influenced by or adopted/modified the regional (basinwide) hydrostratigraphy introduced by Lewis and Hotchkiss (1981) or Feathers and others (1981). These studies noted that although individual sandstone and coal aquifers in the Wasatch Formation and the three members of the Fort Union Formation have limited areal extent and are considered aquifers at the local scale, they are sufficient in number, and hydraulic connection between them sufficient that the lithostratigraphic units (members or formations) as a whole can be considered to be subregional (large part of the basin) or regional (basinwide) hydrogeologic units (Feathers and others, 1981; Lewis and Hotchkiss, 1981; Koch and others, 1982; Bloyd and others, 1986; Hotchkiss and Levings, 1986; Martin and others, 1988; Fogg and others, 1991; Thamke and others, 2014). Some investigators interpret the regional hydrogeologic characteristics of the Wasatch Formation differently. These investigators do not consider the Wasatch Formation to be a regional aquifer because fine-grained rocks with low permeability compose a substantial amount of the formation compared with permeable lithologies (sandstone), and thus, limit hydraulic connection between the individual sandstone aquifers. Consequently, these studies defined the Wasatch Formation as a hydrogeologic unit consisting of numerous local sandstone aquifers with limited/local hydraulic connection because of intervening low-permeability fine-grained rocks or as a leaky confining unit with local aquifers (for example, Lowry and others, 1993; AECOM, Inc., 2009; Ogle and others, 2011).

The regional hydrostratigraphic frameworks developed by Lewis and Hotchkiss (1981) and Feathers and others (1981) were highly influential, and many subsequent hydrogeologic studies of the Wasatch and Fort Union Formations in the PRSB have adopted or modified their frameworks. Lewis and Hotchkiss (1981, sheet 1) identified the uppermost hydrogeologic unit as the Tongue River-Wasatch aquifer (also referred to as the Wasatch-Tongue River aquifer in many studies, and used hereinafter in this report) composed primarily of the Wasatch Formation and Tongue River Member of the Fort Union Formation, but also locally occurring water-saturated and permeable units with limited geographic extent including sandstone and siltstone in the underlying upper parts of the Lebo Shale Member of the Fort Union Formation, overlying Quaternary alluvial and terrace deposits, and overlying isolated erosional remnants of the White River Formation. Sandstone content of the Wasatch-Tongue River aquifer was estimated to average 55 percent. The hydrogeologic unit underlying the Wasatch-Tongue River aquifer was identified as the Lebo confining unit, composed primarily of the massive mudrocks (shale) of the Lebo Shale Member of the Fort Union Formation that give it confining unit characteristics. Despite being composed primarily of mudrocks such as shale that give it confining unit characteristics, the Lebo Shale Member was estimated to average 31 percent sandstone. Below the Lebo confining unit is the Tullock aquifer, composed primarily of the entire Tullock Member, but also locally occurring basal channel sandstone in the bottom of the overlying Lebo Shale Member. Sandstone content of the Tullock aquifer was estimated to average 53 percent. The Tullock aquifer is confined below by the upper Lance confining unit composed of the upper part of the Upper Cretaceous Lance Formation (this confining unit is the upper part of the Hell Creek confining unit in Montana, composed of the upper part of the stratigraphically equivalent Hell Creek Formation). The investigators (Lewis and Hotchkiss, 1981, sheet 1) also noted lithologic variation could result in local "hydrogeologic anomalies" in parts of the PRSB "where confining layers can contain



[1] Compiled from Love and others (1993) and Wyoming Geological Association (2014).

[2] Bearpaw and Lewis Shales present in western Powder River structural basin (PRSB). Pierre Shale present in eastern PRSB and Black Hills uplift area.

[3] Sandstone beds/members within the predominant shale composition may contain aquifers where water-saturated and permeable.

[4] Study conducted at Hilight oilfield in southeastern Campbell County.

[5] Lance-Fox Hills aquifer defined as consisting of the lower Tullock Member, all of the Lance Formation, and the upper Fox Hills Sandstone.

[6] Synthesis of then-current USGS studies and numerous earlier USGS studies cited therein.

[7] Wasatch-Tongue River aquifer can include water-saturated and permeable sandstone in upper part of the underlying Lebo Shale Member (indicated by dashed lines). Aquifer also includes Quaternary alluvial and terrace deposits, clinker, and White River Formation where locally water-saturated and permeable.

[8] Tullock aquifer can include water-saturated and permeable sandstone in the basal part of the overlying Lebo Shale Member (indicated by dashed lines).

[9] Hell Creek Formation is the Montana stratigraphic name for the equivalent Lance Formation in Wyoming.

[10] Upper part of Pierre Shale contains sandstone beds with local aquifers (identified as the upper Pierre aquifer).

[11] Also includes water-saturated alluvium.

[12] Study area extends beyond Powder River structural basin in Wyoming and Montana. Includes part of Fort Union Formation above Wyodak-Anderson coal zone.

[13] Includes part of Fort Union Formation above Wyodak-Anderson coal zone.

[14] Composed of low-permeability rocks underlying and overlying Wyodak-Anderson coal zone. Not present everywhere.

[15] Lance Formation and Fox Hills Sandstone were "assumed to be hydraulically connected and to respond as one aquifer" (Crist, 1991, sheet 1).

[16] Includes numerous coal aquifers in both lithostratigraphic units, including the Wyodak-Anderson coal zone in the Tongue River Member. Alluvial aquifers may be hydraulically connected to the aquifer in some areas.

[17] Wasatch-Tongue River aquifer can include water-saturated and permeable sandstone in upper part of the underlying Lebo Shale Member (indicated by dashed lines).

EXPLANATION

▨ **Rocks absent due to erosion or nondeposition**

〰 **Unconformity**

– – **Not discussed in study**

PRSB **Powder River structural basin**

Figure 7-8. Hydrostratigraphic diagram showing lithostratigraphic and corresponding hydrogeologic units of the lower Tertiary (Wasatch and Fort Union Formations) and Upper Cretacous (Lance Formation and Fox Hills Sandstone) aquifer systems in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana.

sandstone beds that function as local aquifers, just as aquifers can contain shale beds that function as local confining layers." Subsequent investigators combined the hydrogeologic units of Lewis and Hotchkiss (1981) with minor nomenclature changes/modifications into a heterogeneous regional lower Tertiary aquifer system (fig. 7-8; Hotchkiss and Levings, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996; Thamke and others, 2014). This study uses the hydrostratigraphic nomenclature as defined by Lewis and Hotchkiss (1981) and modified by Hotchkiss and Levings (1986) and Thamke and others (2014); however, most physical and chemical hydrogeologic data inventoried for this study were assigned only to formation names (Wasatch and Fort Union Formations), so these data were assigned to broader hydrogeologic units ("Wasatch aquifer" and "Fort Union aquifer") for summaries of these characteristics herein. This study does not include the White River Formation as part of the Wasatch-Tongue River aquifer as defined by Lewis and Hotchkiss (1981).

Feathers and others (1981, fig. II-4) grouped the Wasatch Formation and Tongue River Member of the Fort Union Formation into an aquifer/aquifer system identified as the Wasatch/Fort Union aquifer system, a hydrogeologic unit equivalent to the Wasatch-Tongue River aquifer of Lewis and Hotchkiss (1981; fig. 7-8). Both the Wasatch Formation and the Tongue River Member also were considered to be individual aquifers within the aquifer system, consisting of numerous individual coal and sandstone aquifers within each lithostratigraphic unit (identified as "Wasatch aquifers" and "upper Fort Union aquifers"; fig. 7-8). Below the Wasatch/Fort Union aquifer system, the Lebo Shale Member was defined as an intervening leaky confining unit between the overlying Wasatch-Fort Union aquifer system and an underlying aquifer system identified as the Fox Hills/Lance aquifer system. The Fox Hills/Lance aquifer system was defined as consisting of the Tertiary-age (Paleocene) Tullock Member of the Fort Union Formation and the Late Cretaceous-age Lance Formation and Fox Hills Sandstone. Grouping together of these three units into an aquifer system apparently was influenced by Lowry (1972, 1973) who noted vertical hydraulic connection between the lower part of the Tullock Member and the underlying Lance Formation and Fox Hills Sandstone in the Hilight Oilfield in southeastern Campbell County. All three lithostratigraphic units also were considered by Feathers and others (1981) to be individual aquifers in the Fox Hills/Lance aquifer system—the Tullock Member was identified as an aquifer consisting of numerous individual sandstone aquifers ("lower Fort Union aquifers"), whereas the Lance and Fox Hills aquifers were named after their respective lithostratigraphic unit (fig. 7-8). Below the Fox Hills/Lance aquifer system, the Upper Cretaceous Pierre, Bearpaw, or Lewis Shales compose a thick underlying regional confining unit (fig. 7-8).

Numerous studies contemporary with and subsequent to Lewis and Hotchkiss (1981) and Feathers and others (1981) examined the potential effects of coal mining and (or) CBNG development on the shallow groundwater system in the eastern PRSB consisting of the Wyodak-Anderson coal aquifer and overlying/underlying sandstone aquifers in the Wasatch and Fort Union Formations. Many of these studies modified the hydrostratigraphic nomenclature of one or both of these studies to emphasize study of the Wyodak-Anderson coal aquifer and potential hydraulic connection with overlying sandstone aquifers in the Wasatch Formation and overlying/underlying sandstone aquifers in the Tongue River Member that contains the coal aquifer (fig. 7-8; for example, Bloyd and others, 1986; Martin and others, 1988; Peacock, 1997; Wyoming Water Resources Center, 1997; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002; AECOM, Inc., 2009, 2014; Ogle and others, 2011). The Wyodak-Anderson coal zone (and associated aquifer) in these studies was identified as a separate individual subregional aquifer within the Tongue River Member, in contrast to the discontinuous lenticular sandstone lenses and beds with limited geographic extent that compose individual aquifers in both the Wasatch and Fort Union Formations (and collectively compose the associated regional aquifers within both lithostratigraphic units) (some of these shown on fig. 7-8). Consequently, the Wyodak-Anderson coal aquifer in these studies can be interpreted to be a subaquifer within the regional Wasatch-Tongue River aquifer and that interpretation is adopted herein (fig. 7-8). Some studies defined additional coal subaquifers within the Tongue River Member of the Fort Union Formation (Wasatch-Tongue River aquifer) for groundwater modeling purposes (Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; AECOM, Inc., 2009, 2014; AECOM and Environmental Simulations, Inc., 2009).

Recharge, groundwater flow, and discharge

Although the mechanisms, location, and amount of surficial groundwater recharge to the upper part of the lower Tertiary aquifer system have been interpreted differently between studies, most agree that recharge is provided primarily by direct infiltration and percolation of precipitation (snowmelt and rain), water in topographic depressions (playas, reservoirs, and CBNG impoundments), and ephemeral and perennial streamflow losses on formation outcrops (Hagmaier, 1971; Brown, 1980; Feathers and others, 1981; Bloyd and others, 1986; Hotchkiss and Levings, 1986; Lenfest, 1987; Lowry and Rankl, 1987; Martin and others, 1988; Rankl and Lowry, 1990; Fogg and others, 1991; Peacock, 1997; Wyoming Water Resources Center, 1997; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002; AECOM, Inc., 2009, 2014; Aurand, 2013; Bednar, 2013; Long and others, 2014). This recharge may be enhanced in outcrop areas with more permeable surficial lithologies such as sandstone or clinker, and in topographically elevated areas with greater precipitation, especially along the east, south, and west margins of the PRSB. In addition, the topographically elevated areas commonly are outcrop areas for more erosionally resistant and permeable lithologies (sandstone and clinker) that are more likely to accept recharge. Diffuse recharge estimates vary between studies, but most range from less than 1 to 5 percent of mean annual precipitation, with many of the studies indicating less than 1 percent (for example, Brown, 1980; Feathers and others, 1981; Jordan and others, 1984; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002;).

A recent U.S. Geological Survey (USGS) study constructed a basinwide (PRSB in both Wyoming and Montana) water budget for the lower Tertiary aquifer system and underlying Upper Cretaceous aquifer system (composed of the underlying Upper Cretaceous Lance Formation and Fox Hills Sandstone) (Aurand, 2013; Bednar, 2013; Long and others, 2014). Focused recharge (stream infiltration, or streamflow loss) and diffuse recharge (precipitation recharge) were estimated as part of the water budget constructed for the study (table 7-1). Historical streamflow measured at major streams and rivers during low-flow conditions was analyzed to identify gaining stream reaches receiving groundwater discharge (base flow) and losing stream reaches providing recharge to underlying aquifers (stream infiltration) (fig. 7-9). Many stream and river reaches in the PRSB of Wyoming and Montana were interpreted to be gaining reaches, with losing reaches generally more common in the northern and western parts of the basin. Recharge from stream infiltration was estimated to be about 1,200 cubic ft per second (ft³/s), representing the majority (80 percent) of total groundwater recharge (table 7-1). Initial estimates of total stream infiltration using the streams and rivers with streamflow records of sufficient quality for analysis were not large enough to balance inflows and outflows. The investigators concluded that additional unaccounted for stream infiltration necessary to balance inflows and outflows likely occurs primarily from other streams and rivers without measured streamflow records and during high-flow periods. Long and others (2014) cited a study by McCallum and others (2014) that con-

Table 7-1. Estimated average groundwater recharge and discharge components for 1981–2005 for the total control volume of the combined lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin, Wyoming and Montana (modified from Long and others, 2014).

[ft³/s, cubic feet per second; <, less than; --, not applicable]

Recharge or discharge component	Combined aquifer systems control volume[a]		Period of record
	ft³/s	Percent[b]	
Groundwater recharge			
Precipitation recharge	221	15	1981–2005
Stream infiltration	1,200	80	1900–2005[c]
Irrigation recharge	80	5	1981–2005
Total recharge	1,500	100	--
Groundwater discharge			
Discharge to streams	1,380	92	1900–2005[c]
Groundwater withdrawal	109	7	1981–2005
Groundwater outflow to the Williston Basin	8	<1	--
Total discharge	1,500	100	--

[a] The control volume areal extent in Wyoming and part of Montana is shown on figures 7–7, 7–10, and 7–13.

[b] The percentage of total recharge or total discharge.

[c] Data through 2011 were used for about 4 percent of the streamgages.

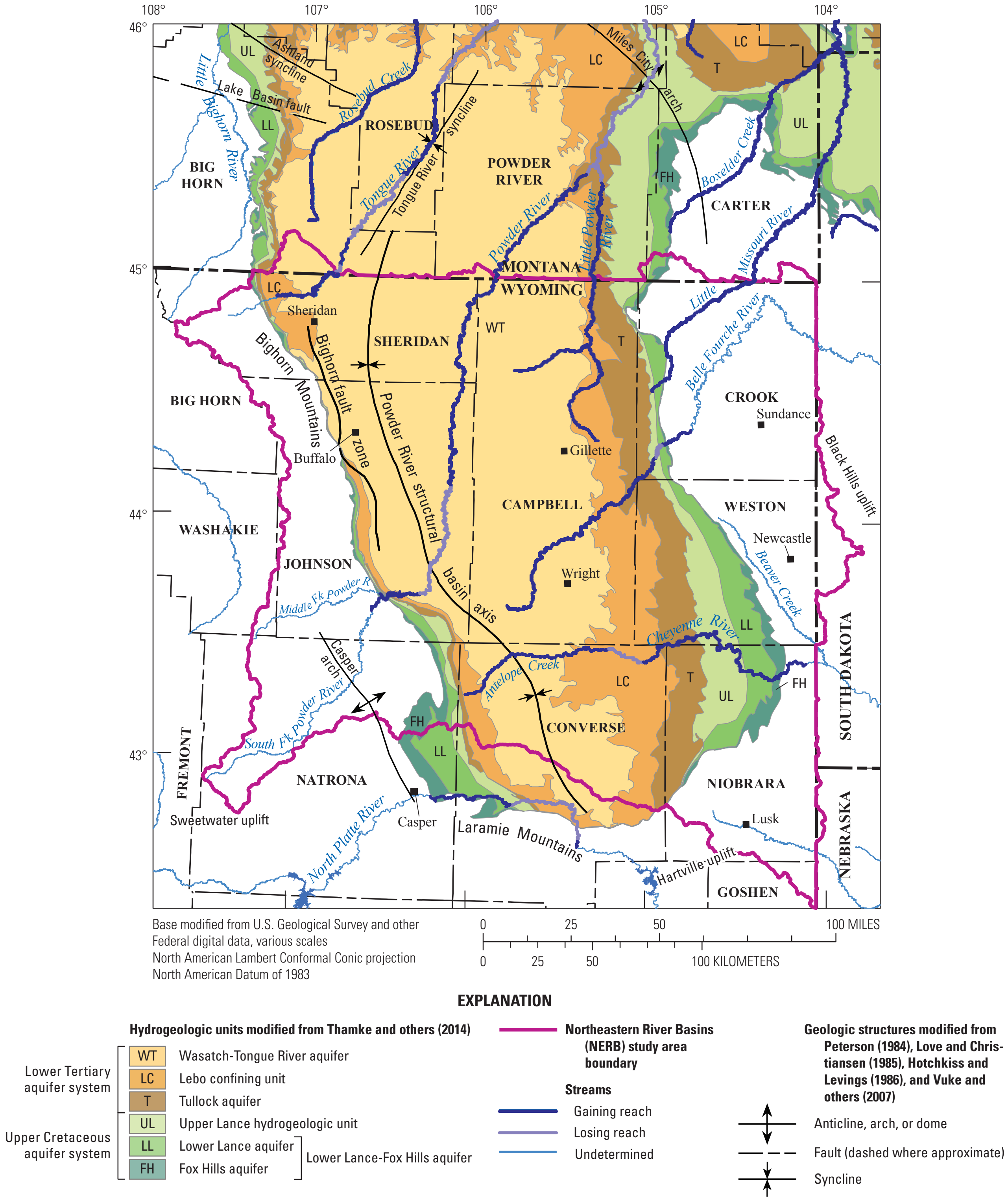


Figure 7-9. Gaining and losing stream reaches overlying the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin and adjacent areas, Northeastern River Basins study area, Wyoming and Montana (modified from Long and others, 2014).

cluded stream-infiltration rates in semiarid and arid environments generally are highest during high-flow periods and that large flow events may account for a substantial amount of total stream infiltration to groundwater in semiarid and arid environments. Clinker underlying streams in many watersheds capable of accepting substantial recharge during high streamflow and faults underlying streams on the western mountain-basin margin near the Bighorn Mountains also were speculated to contribute to additional unaccounted for stream infiltration.

Precipitation recharge was estimated by Long and others (2014) using a numerical soil-water-balance (SWB) model (Dripps and Bradbury, 2007; Westenbroek and others, 2010). Estimated average precipitation recharge for the PRSB was 0.8 percent of mean annual precipitation for 1981–2005 [0.12 inches per year (in/yr) or 221 ft^3/s], and varied from 0 to 5.8 in/yr in different parts of the basin (table 7-1; fig. 7-10). This precipitation recharge represented 15 percent of total recharge to the lower Tertiary and Upper Cretaceous aquifer systems. Recharge from precipitation generally increased with increasing elevation. Areas near the Bighorn Mountains on the western side of the basin, Laramie Mountains on the southwestern side of the basin, and northwest of the Tongue River received the highest estimated precipitation recharge (fig. 7-10). Overall, the amount of water available for runoff to streams or recharge to groundwater is small because potential evapotranspiration is much higher than precipitation throughout much of the PRSB (Wolock, 2003; Long and others, 2014). Estimated precipitation recharge for 1981–2005 was 0 for about 63 percent of the PRSB extent (fig. 7-10). The Wasatch-Tongue River aquifer receives much of this precipitation recharge because it crops or subcrops out over much of the PRSB. The remaining source of groundwater recharge was interpreted to be from irrigation, and represented only about 5 percent of total groundwater recharge (table 7-1). The relative percentages of recharge contributed from precipitation and streamflow losses are similar to estimates for both aquifer systems in the PRSB determined by Hotchkiss and Levings (1986) using a regional steady-state groundwater flow model. Recharge from sources such as losing streams was estimated to be about 71 percent of recharge, and recharge from precipitation was estimated to be about 29 percent of total recharge.

Recharge to the Wyodak-Anderson coal aquifer in the eastern and central PRSB has been interpreted by most studies to occur primarily through clinker associated with outcrops of the coal zone located along the eastern basin margin (Lowry and Cummings, 1966; Whitcomb and others, 1966; Davis, 1976; Davis and Rechard, 1977; Stephenson, 1982; Daddow, 1986; Nielsen, 1987; Martin and others, 1988; Heffern and Coates, 1999; Bartos and Ogle, 2002; Pearson, 2002; Frost and Brinck, 2005; Brinck and others, 2008; Campbell and others, 2008; Flores and others, 2008; Rice and others, 2008; Quillinan and Frost, 2012). Bates and others (2011) concluded that waters along the eastern basin margin near the coal outcrop represented a mixture of eastern basin recharge (as indicated by earlier studies) with deeper circulating groundwater. The investigators also concluded that the Wyodak-Anderson coal aquifer in the central part of the basin was recharged primarily from the southern basin margin, in contrast to most other studies suggesting recharge primarily from the eastern basin margin. Along the northwestern basin margin in Wyoming, coal aquifer waters likely contain some high elevation recharge from the Bighorn Mountains, with flow patterns likely affected by locally occurring faults (Bates and others, 2011). Overlying and underlying sandstone aquifers likely provide some interaquifer leakage/recharge to the Wyodak-Anderson coal aquifer where geologic conditions and vertical hydraulic gradients are favorable for vertical groundwater movement (Brown, 1980; Stephenson, 1982; Applied Hydrology Associates, Inc. and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002); however, some investigators note that the predominant fine-grained lithology of the rocks above the Wyodak-Anderson coal zone prevents much vertical recharge to the coal aquifer, even in areas with substantial vertical hydraulic gradients (Davis and Rechard, 1977; Collentine, 1982). Some degree of hydraulic isolation of individual coal aquifers within the Wyodak-Anderson coal zone from one another and from underlying and overlying strata is suggested by waters with unique isotopic signatures (Quillinan and Frost, 2014). Geologic conditions likely to enhance the potential for recharge from overlying aquifers include leakage from sandstone beds containing aquifers located immediately above the coal aquifer, or separated from the coal aquifer by small thicknesses of intervening fine-grained rocks, and (or) the presence of locally occurring faults or fractures (Stephenson, 1982; Applied Hydrology Associates, Inc. and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002). Recharge also may occur where coals subcrop below water-saturated alluvium in stream valleys; discharge from the aquifer also may occur in these areas (Davis, 1976; Davis and Rechard, 1977; Brown, 1980; Martin and others, 1988). Discharge from the Wyodak-Anderson coal aquifer also is to springs, groundwater wells, and leakage to underlying and overlying hydrogeologic units (Brown, 1980; Feathers and others, 1981; Martin and others, 1988).

Groundwater movement and flowpaths in the groundwater system composed of the Wasatch and Fort Union

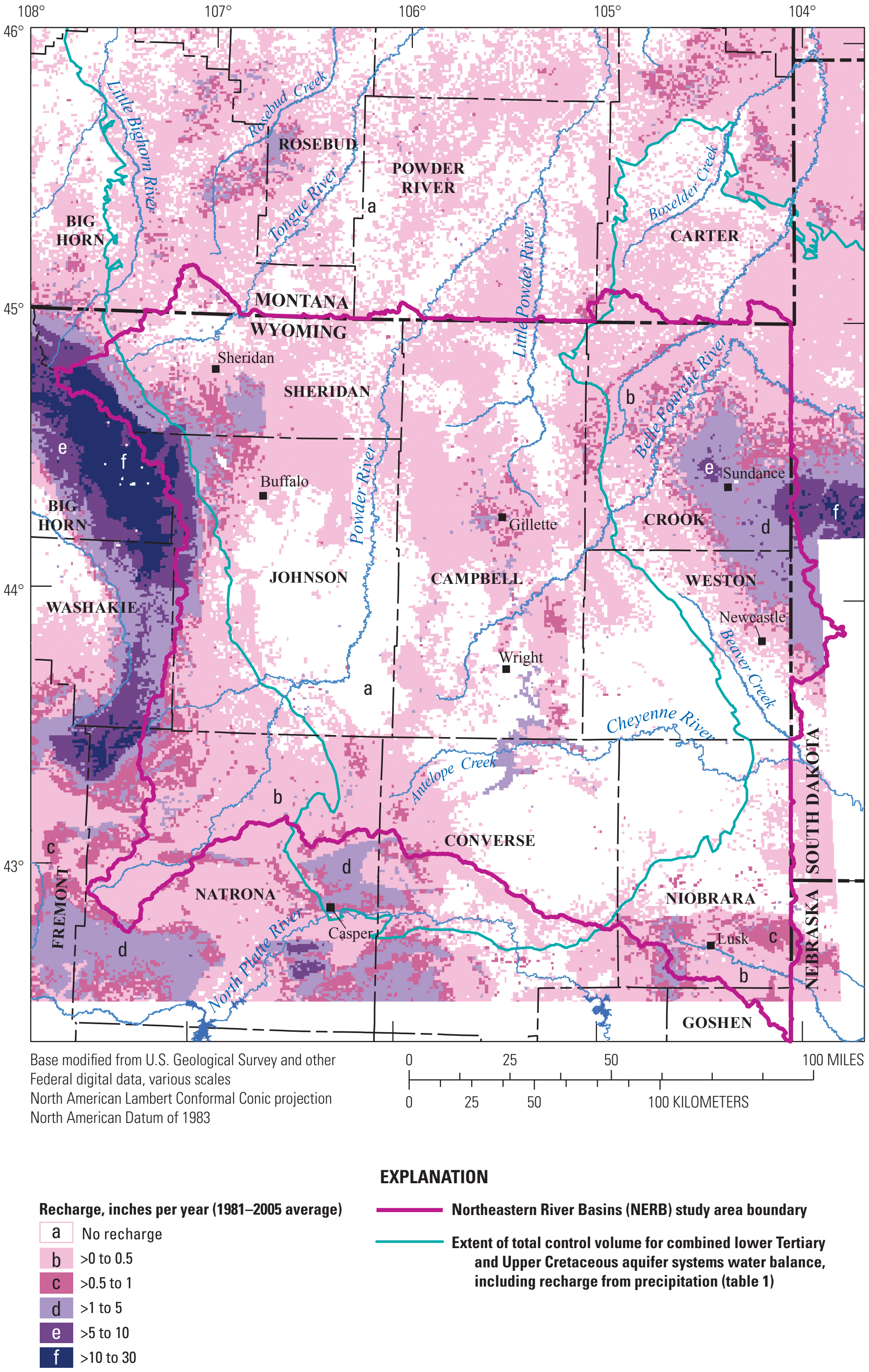


Figure 7-10. Recharge from precipitation in the vicinity of the Northeastern River Basins study area, Wyoming and Montana (modified from Long and others, 2014).

Formations in the PRSB have been interpreted differently among studies. Investigators differ on the amount and location of local, intermediate (subregional), and regional groundwater flow as well as the amount of vertical flow, both within and between the individual hydrogeologic units composing the lower Tertiary aquifer system. Complicating interpretation of groundwater movement and flowpaths is that the majority of groundwater-level measurements available for use by most studies were obtained from groundwater wells less than 1,000-ft deep (commonly less than 500 ft), thus penetrating only the upper part of the several thousand-foot thick aquifer system. In addition, studies examining groundwater movement and flowpaths varied in geographic extent. Hydrogeologic studies with limited (local) geographic extent do not address the extent to which local hydrogeologic conditions are representative of conditions elsewhere in the PRSB, whereas regional studies may be too "coarse" to identify and interpret local groundwater flow systems and show interaction with streams (Lindner-Lunsford and Wilson, 1992).

Studies generally conclude that some amount of groundwater movement through local to intermediate flow systems occurs in the shallowest part of the aquifer system that includes all or part of the Wasatch and Fort Union Formations, although conclusions regarding the location and amount of flow within and between lithostratigraphic/hydrogeologic units differ between investigators (Hagmaier, 1971; King, 1974; Feathers and others, 1981; Hotchkiss and Levings, 1986; Martin and others, 1988; Rankl and Lowry, 1990; Lowry and others, 1993; Peacock, 1997; Wyoming Water Resources Center, 1997; Applied Hydrogeology, Inc. and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002; AECOM, Inc., 2009, 2014; Thamke and others, 2014). Most of these studies also infer or explicitly state that flow systems of different sizes (local, intermediate, and regional) occur and likely are superimposed on one another in the various hydrogeologic units of the lower Tertiary aquifer system. With this interpretation, groundwater moves horizontally and vertically through the shallowest and most dynamic part of the aquifer system in local to intermediate flowpaths with recharge at topographic highs and discharge areas at topographic lows (topographically controlled flow system), whereas groundwater in the deeper part of the aquifer system moves in long regional flowpaths that may differ from local and intermediate flowpaths. However, these studies sometimes differ as to where (geographic location and depth) and in which lithostratigraphic/hydrogeologic units (or parts or combinations of lithostratigraphic/hydrogeologic units) these flow systems occur, as well as the relative amount of flow within and between the units and the amount and location of groundwater discharge from the system (Hagmaier, 1971; Hotchkiss and Levings, 1986; Peacock, 1997; Wyoming Water Resources Center, 1997; Bartos and Ogle, 2002; Applied Hydrogeology, Inc. and Greystone Environmental Consultants, Inc., 2002; AECOM, 2009, 2014; Long and others, 2014; Thamke and others, 2014). Many of these studies interpret regional groundwater flow to be very small in comparison with local flow, especially in the shallowest part of the system (for example, Brown, 1980; Feathers and others, 1981; Bloyd and others, 1986; Rankl and Lowry, 1990; Lowry and others, 1993); furthermore, some of these studies suggest most of this local flow occurs in a series of isolated local groundwater flow systems where horizontal rather than vertical flow dominates, reflecting hydraulic isolation of individual sandstone aquifers from one another by intervening fine-grained mudrocks that compose a substantial percentage of the Wasatch and Fort Union Formations.

Generalized potentiometric-surface maps showing apparent groundwater flow in the Wasatch-Tongue River and Tullock aquifers in Wyoming and Montana were constructed by Hotchkiss and Levings (1986). Thamke and others (2014, appendix fig. 1-2) modified these maps to improve contour density, and both are reproduced herein as figures 7-11 and 7-12. Potentiometric-surface contours indicate generally northward groundwater flow for both aquifers in much of the Wyoming part of the PRSB, although contours are not shown for the Tullock aquifer in most of the southern part of the PRSB in Wyoming where few groundwater-level measurements were available because of deep aquifer burial.

Potentiometric contours constructed for the Wasatch-Tongue River aquifer indicate topographically controlled local and intermediate groundwater flow towards and discharge into major perennial streams, primarily parts of the Powder, Tongue, and Belle Fourche Rivers, and Antelope Creek (fig. 7-11). In the southern PRSB, groundwater flow in the Wasatch-Tongue River aquifer generally is towards the east, and some groundwater discharge to Antelope Creek is indicated by potentiometric-surface contours, gaining stream reaches, and hydraulic head differences (Long and others, 2014). Potentiometric contours indicate groundwater in the Wasatch-Tongue River aquifer generally flows towards the east in the central PRSB, and some groundwater discharge to the Belle Fourche River is indicated.

Potentiometric contours constructed for the Tullock aquifer are more subdued than the overlying Wasatch-Tongue River aquifer and indicate groundwater generally flows northerly to northeastward for the part of the PRSB

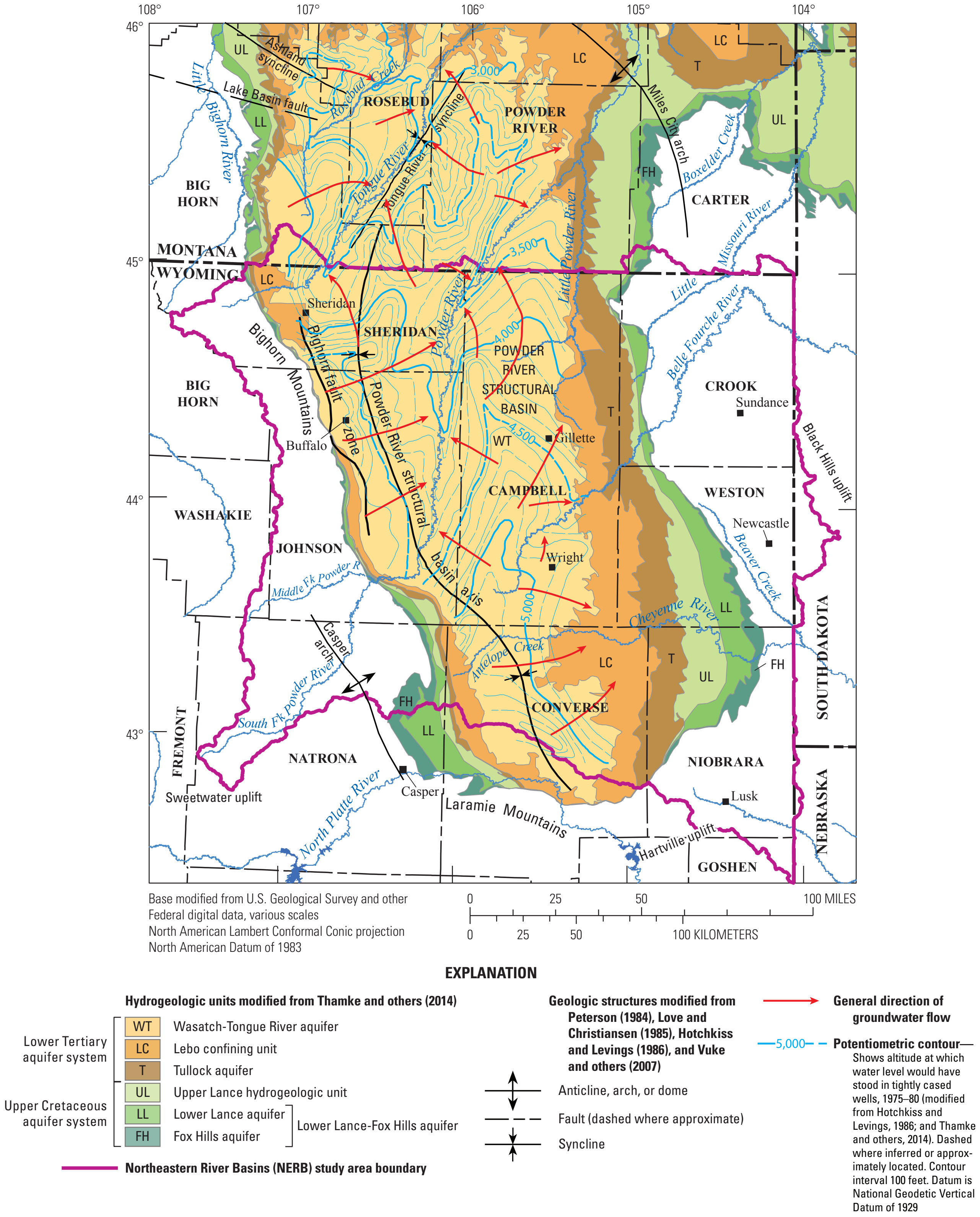


Figure 7-11. Potentiometric surface of the Wasatch-Tongue River aquifer in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

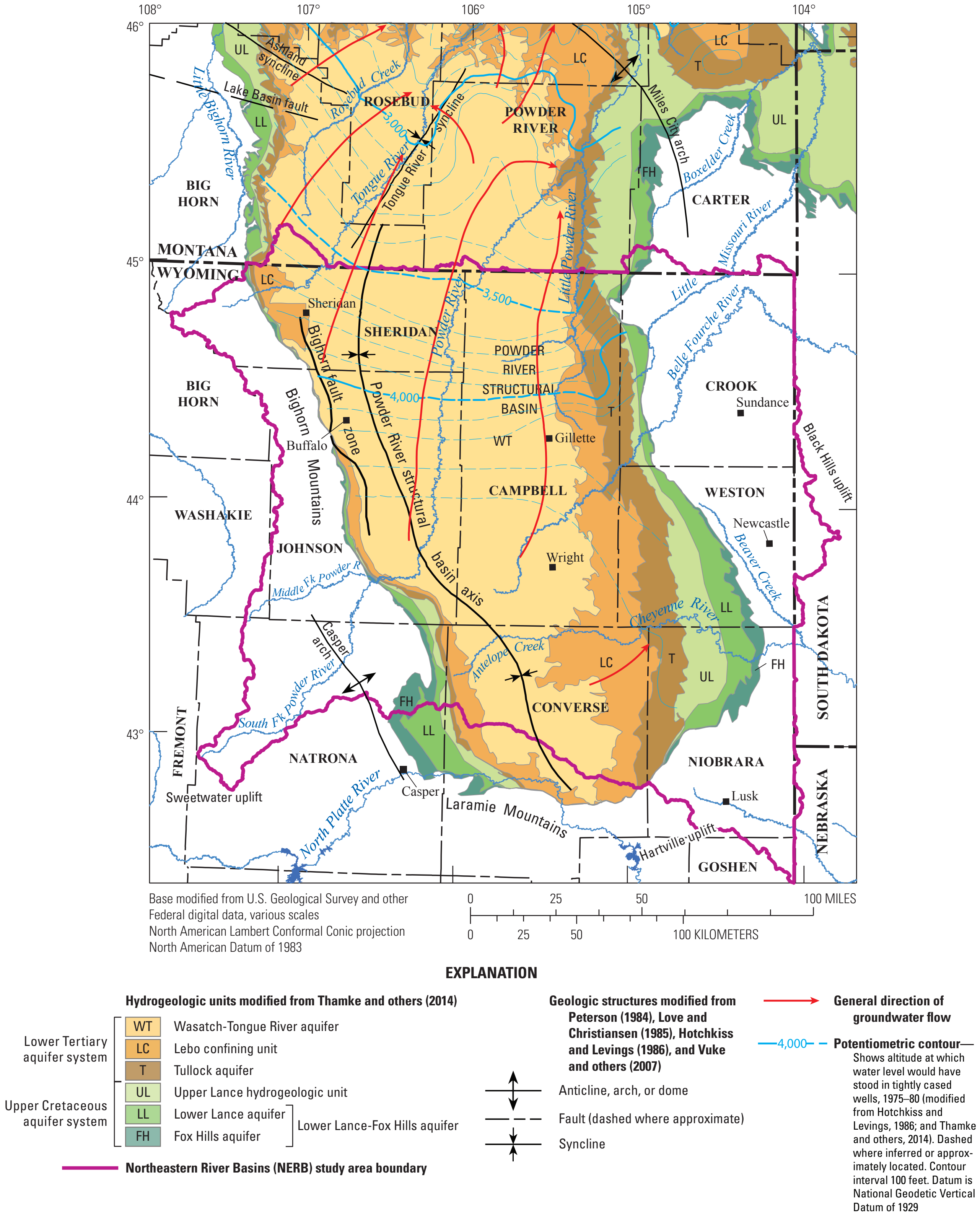


Figure 7-12. Potentiometric surface of the Tullock aquifer in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

within Wyoming (fig. 7-12). Groundwater discharge to the Powder River also is indicated.

Long and others (2014) used both potentiometric-surface maps to calculate the difference in hydraulic head between the two aquifers. The calculated difference in hydraulic head ranged from -201 to 873 ft, with a mean of 311 ft (Long and others, 2014, table 6). The substantial difference in hydraulic head between the two aquifers indicates hydraulic separation by the intervening Lebo confining unit. The calculated hydraulic gradient generally is positive between aquifers, indicating a downward hydraulic gradient, but the calculated hydraulic gradient is negative along some reaches of the Tongue and Powder Rivers, indicating an upward hydraulic gradient.

Potentiometric-surface maps of the Wyodak-Anderson coal aquifer constructed using groundwater levels measured prior to coal mining and CBNG development indicate groundwater in the aquifer in the north and central parts of the eastern PRSB initially flows west, away from the coal outcrops and associated clinker presumed to provide recharge (fig. 7-7), and then flows towards the north and northwest, the direction of maximum hydraulic gradient (fig. 7-13; Bloyd and others, 1986; Daddow, 1986; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002, fig. 3-3; AECOM, Inc., 2009, 2014). In the southernmost part of the PRSB, groundwater generally flows east, away from coal outcrops and associated clinker presumed to provide recharge (fig. 7-13). The direction of groundwater flow in some areas of the Wyodak-Anderson coal aquifer may differ from pre-mining conditions shown on these maps as a result of groundwater-level declines caused by dewatering associated with coal mining and CBNG development (Meyer, 1999; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; AECOM, Inc., 2009, 2014; Taboga and others, 2015, 2017, and references therein).

Discharge from the lower Tertiary aquifer system occurs naturally through gaining streams, evapotranspiration, springs, seeps, and vertical interaquifer leakage/flow, and anthropogenically through pumpage of groundwater from wells (Hagmaier, 1971; Bloyd and others, 1986; Hotchkiss and Levings, 1986; Lowry and Rankl, 1987; Rankl and Lowry, 1990; Martin and others, 1988; Fogg and others, 1991; Peacock, 1997; Wyoming Water Resources Center, 1997; Applied Hydrology Associates, Inc., and Greystone Environmental Consultants, Inc., 2002; Bartos and Ogle, 2002; AECOM, Inc., 2009, 2014; Aurand, 2013; Bednar, 2013; Long and others, 2014; Meredith and Kuzara, 2012; Meredith, 2016). The amount and location of natural groundwater discharge has been subject to different interpretations. The majority of studies concluded that groundwater in local, intermediate, and regional flow systems flows towards and discharges to stream valleys (topographic lows), contributing to streamflow and (or) hydraulically connected alluvial aquifers. In contrast, several studies concluded that although many of these studies used potentiometric-surface maps to indicate there was a substantial component of intermediate to regional vertical flow towards and discharge to major streams, analysis of streamflow records indicated there was little or no evidence of groundwater contribution to streamflow in many of these areas, especially from intermediate and regional flow systems (Armentrout and Wilson, 1987; Lowry, Wilson, and others, 1986; Rankl and Lowry, 1990; Lowry and others, 1993). Rankl and Lowry (1990) concluded that groundwater contribution to streamflow, where present, was primarily from local rather than intermediate or regional flow systems, and that local systems in alluvium and clinker have a much larger effect on PRSB streamflow than intermediate or regional flow systems. Furthermore, they concluded that much of the groundwater discharge from bedrock aquifers to stream valleys in the PRSB occurs above streams, and thus does not contribute to streamflow or alluvial aquifer recharge. The investigators also concluded that streamflow losses contribute recharge primarily to associated alluvial aquifers rather than underlying bedrock aquifers, and that base flow in the Powder River was difficult to detect using streamflow analysis because most of the small amount that occurs is lost to evapotranspiration. Similarly, Ringen and Daddow (1990) concluded that the stream/alluvial aquifer system of the Powder River was largely isolated from underlying bedrock aquifers. In contrast, the recent USGS study described previously herein (Aurand, 2013; Bednar, 2013; Long and others, 2014) conducted an extensive analysis of streamflow and concluded that groundwater contributes to streamflow of many reaches of major streams in the PRSB overlying alluvium and the lower Tertiary and Upper Cretaceous aquifer systems (see gaining stream reaches identified in blue on fig. 7-9).

Groundwater-flow models

In response to coal and uranium mining and CBNG development, numerous groundwater-flow models have been constructed for all or parts of the lower Tertiary aquifer system in the PRSB. Models were constructed to examine the groundwater-flow system at the local (individual coal or uranium mines and immediately surrounding areas), intermediate (subregional, or substantial part of the structural basin), and regional (entire structural basin) scales. Most of the modeling efforts emphasize study of the eastern part of the structural basin in Wyoming where all of the coal mining and a

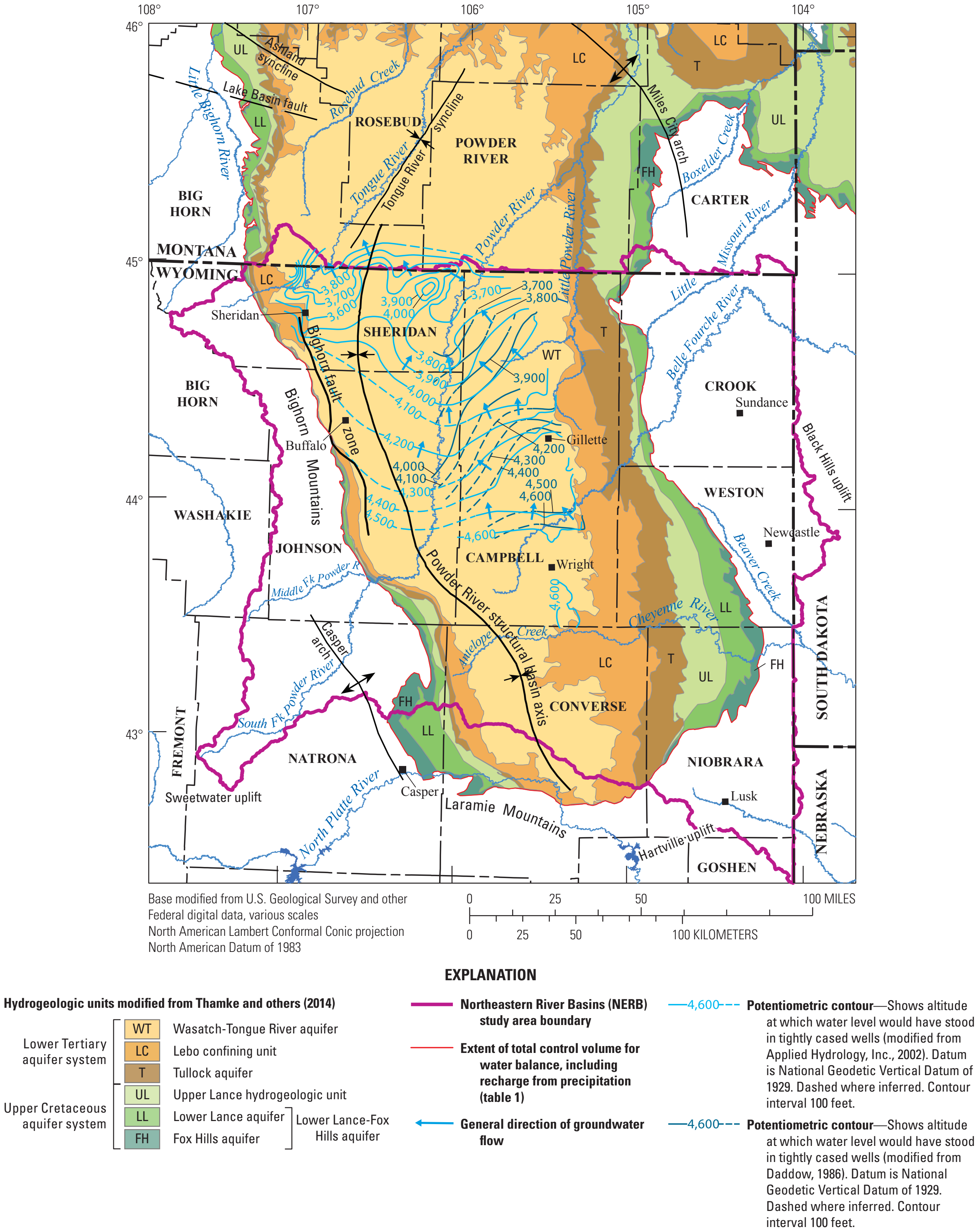


Figure 7-13. Potentiometric surface of the Wyodak-Anderson coal aquifer in the Powder River structural basin prior to coal mining and coalbed natural gas development, Northeastern River Basins study area, Wyoming and Montana.

substantial part of the CBNG development occurs. This section of the report identifies and briefly describes subregional- and regional-scale groundwater-flow models of the lower Tertiary aquifer system. The numerous local-scale groundwater-flow models constructed to predict the hydrologic impacts of surficial (strip) mining at individual coal mines are not discussed herein.

Koch and others (1982) constructed regional and subregional groundwater-flow models of the lower Tertiary and Upper Cretaceous aquifer systems in the Wyoming part of the PRSB, although most of the model extent is associated with the lower Tertiary aquifer system. Both the regional and subregional groundwater-flow models were constructed using modified versions of the finite-difference model of Prickett and Lonnquist (1971) to evaluate the effects of surficial coal mining (strip mining) on groundwater levels and streamflow. The regional groundwater-flow model was constructed to simulate most of the large aquifer system extent (33,000 mi^2) in the basin, but only to a depth of 700 ft below land surface. The aquifer systems in the regional model were simulated using a single aquifer model layer, and were assumed to be one large, homogenous, unconfined aquifer with uniform permeability without regard to individual lithologic/lithostratigraphic/hydrostratigraphic units. An underlying 1-ft thick leaky confining unit was included below the aquifer layer to represent the bottom of the model. Coarse model scale (38.5 mi.^{2} model cells) and assumption of a regionally continuous groundwater-flow system within the single model layer were used to justify these approaches to regional model construction. A steady-state model was constructed and calibrated, and then predictive transient simulations were made to evaluate a hypothetical pre- and post-coal mining scenario assuming construction of three large mines along the easternmost extent of the Wyodak-Anderson coal zone. Model simulation led the investigators to conclude that the hypothetical coal mines likely would have local, rather than regional, effects on the regional flow system. Specifically, the investigators concluded that groundwater-level drawdown in the immediate vicinity of the mines was likely to be locally large but limited to within 40 kilometers (about 25 mi.), stream base flow would be only slightly reduced, and flow in the Powder and Belle Fourche Rivers would be reduced 1.5 and 3 percent, respectively. Upon completion of the regional groundwater-flow model and associated transient simulations, an intermediate-scale (subregional) model with geographic extent coincident with Campbell County was developed to facilitate more detailed simulation of potential hydrologic effects of mining of the Wyodak coal bed in the Gillette area. The intermediate-scale model was constructed differently than the regional model, with an emphasis on the Wyodak-Anderson coal aquifer and aquifers in overlying strata (identified collectively as overburden). A two-layer model was constructed with finer grid spacing than the regional model to improve evaluation of localized mining effects, with the bottom layer representing the Wyodak-Anderson coal aquifer and an overlying confining bed/unit, and an overlying second model layer representing all overburden aquifers. Like the regional model, a steady-state model was developed and calibrated, and then transient simulations were conducted to evaluate potential hydrologic effects from three hypothetical surficial coal mines along the easternmost extent of the Wyodak-Anderson coal zone. Simulation results were similar to the regional model and indicated localized, rather than regional, groundwater-level declines. Maximum extents of predicted groundwater-level drawdowns from the coal mines were as much as 6 mi to the west for the overburden aquifers and 8 mi to the west for the Wyodak-Anderson coal aquifer.

Bloyd and others (1986) attempted to construct a subregional groundwater-flow model of the upper part of the lower Tertiary aquifer system (units above the Tullock aquifer, including the Wyodak-Anderson coal aquifer) for a 4,400-mi^2 area that included most of Campbell County and small parts of adjacent counties. Constructed using a USGS finite-difference model [Trescott (1975), Trescott and Larson (1976), and Trescott and others (1976)] which was a precursor to the USGS finite-difference model MODFLOW (McDonald and Harbaugh, 1988) to evaluate the effects of surficial coal mining on groundwater levels and streamflow, the groundwater-flow model was ultimately unsuccessful because the steady-state groundwater-flow model could not be calibrated. The finite-difference model software selected for simulation was the first “production” version of general-purpose groundwater modeling computer code distributed by the USGS. Failure of the groundwater-flow model/modeling effort was attributed to insufficient quantity and quality of data to define spatially variable aquifer properties, hydraulic head distribution within and between aquifers, and rates of groundwater recharge and discharge.

Unlike all prior and subsequent groundwater-flow models of the lower Tertiary aquifer system constructed to date (2016), Hotchkiss and Levings (1986) constructed a regional model to simulate flow throughout the aquifer system’s entire vertical and lateral (geographic) extent in the PRSB in both Wyoming and Montana. In addition, the underlying Upper Cretaceous aquifer system (composed of the Lance Formation and Fox Hills Sandstone) was simulated for the same area. The USGS precursor to MODFLOW [finite-difference model of Trescott (1975), Trescott and Larson (1976), and Trescott and others

(1976)] was used to construct a five-layer model with an area of 42,000 mi² (using 36-mi² cell size) to simulate flow in the lower Tertiary and Upper Cretaceous aquifer systems. Model layers defined for the lower Tertiary aquifer system coincided with the investigators' definition of hydrogeologic units described previously in the "Regional Hydrostratigraphy" section herein (and adopted as part of this study with minor nomenclature modifications from Thamke and others, 2014). A steady-state model was constructed, calibrated to available and estimated regionally adjusted hydrogeologic data, and then refined using sensitivity analysis and multiple simulations. The resulting final steady-state model then was used to construct a water budget (mass balance) for both aquifer systems, including estimates of inflows and outflows for all hydrogeologic units. Recharge from precipitation was estimated to contribute about 29 percent of total recharge (65.26 ft³/s) to both aquifer systems and about 71 percent (157.60 ft³/s) was derived from "recharge to constant heads such as would occur in areas of losing streams" (Hotchkiss and Levings, 1986, p. 66). Mean annual recharge from precipitation was estimated to be about 0.26 percent of mean annual precipitation (0.0245 in/yr). Topographically elevated areas were concluded to contribute larger amounts of recharge than lower lying areas, especially along uplifts surrounding the basin margin such as the Bighorn Mountains; streamflow losses in these topographically elevated areas were interpreted to contribute substantially to aquifer recharge. Total discharge from the aquifer system (222.39 ft³/s) was estimated to be nearly equal to total recharge (222.86 ft³/s). The investigators concluded that the model was applicable for regional rather than localized applications, but that insights gained as part of the modeling process could be used to develop groundwater-flow models for smaller (subregional or local) parts of the basin.

Peacock (1997) and the Wyoming Water Resources Center (1997) constructed a subregional groundwater-flow model of the upper part of the lower Tertiary aquifer system for a 790-mi² area in the Little Thunder Creek drainage basin east of the city of Wright, Wyoming. The model was developed to simulate current and potential future impacts from three existing surficial coal mines and downdip CBNG development, and to develop methods to evaluate new or expanded development in the study area or other parts of the PRSB. The hydrostratigraphic framework of Lewis and Hotchkiss (1981) was adopted and modified for creation of model layers. Specifically, the Wasatch-Tongue River aquifer was divided into additional hydrogeologic/hydrostratigraphic units to improve simulation of the hydraulic connection between the Wyodak-Anderson coal aquifer and overlying sandstone aquifers in the Wasatch Formation (identified as Wasatch aquifer). A steady-state finite-difference groundwater-flow model was constructed using the then-current version of MODFLOW (McDonald and Harbaugh, 1988), calibrated to hydrogeologic data obtained from Wyoming Department of Environmental Quality surficial coal mining permits, and then refined using sensitivity analysis and multiple simulations. The resulting final steady-state model then was used to simulate impacts (groundwater-level declines) from past to then-current surficial coal mining. Several simulations then were used to predict the amount and location (geographic extent) of future groundwater-level declines from surficial coal mining alone and in combination with CBNG development. Finally, the amount of time for groundwater-level recovery after these activities ceased was predicted. The investigators also noted that the pre-mining aquifer system consisting of the Wyodak-Anderson coal aquifer and the overlying Wasatch aquifer would be replaced by a single "backfill aquifer."

In support of a BLM Environmental Impact Statement (EIS) examining oil and gas development in the PRSB (Bureau of Land Management, 2003), Applied Hydrology Associates, Inc., and Greystone Environmental, Inc. (2002) constructed a regional groundwater-flow model to simulate groundwater flow in the lower Tertiary aquifer system in Wyoming and a small part of southern Montana. After completion of the regional model, two smaller subregional models were constructed for the eastern parts of the basin. Both the regional and subregional groundwater-flow models were constructed using MODFLOW-96 (Harbaugh and McDonald, 1996). The hydrostratigraphic frameworks of Lewis and Hotchkiss (1981) and Feathers and others (1981) were modified for creation of 17 model layers. For the regional model, the Wasatch Formation was divided into seven model layers representing sandstone aquifers and confining units, and the Fort Union Formation was divided into nine model layers representing sandstone aquifers, confining units, and four defined coal aquifers. A uniform grid spacing of one-half mile was used for the entire model extent. A steady-state model was constructed, calibrated to pre-mining groundwater levels obtained from numerous sources and Powder River and associated tributary base flows, and subsequently refined by varying hydrogeologic properties. Upon completion of steady-state model calibration, transient simulations were conducted and modeled groundwater-level drawdowns were compared with actual drawdowns for post-mining and post-CBNG development conditions; calibration of the transient model was conducted iteratively by adjustment of various model inputs. Sensitivity analysis was conducted for both the steady-state and transient models and then various developmental scenarios were conducted to evaluate/predict hydrologic impacts to the lower Tertiary aquifer system. The two subregional groundwater flow models were developed at much smaller scales to complement the regional model and evaluate certain hydrogeologic aspects of CBNG development. One subregional model was constructed for an area with a relatively long history of CBNG development to evaluate confining unit hydraulic properties that affect projections of shallow aquifer and coal aquifer drawdown and recovery after the end of CBNG pumping. The second subregional model was constructed to evaluate the effects of infiltration from CBNG impoundments and adjacent streamflows on groundwater levels in shallow Wasatch Formation sandstones in an area where surficial discharge of CBNG produced waters likely would be limited by regulators because of poor groundwater quality.

AECOM, Inc. (2009) constructed a regional groundwater-flow model of the lower Tertiary aquifer system for the area of surficial coal mining in the eastern PRSB. The purpose of the model, identified as the Coal Mine Groundwater Model (CMGM), was to provide a tool to evaluate/predict hydrologic impacts to the upper part of the lower Tertiary aquifer system as a result of combined surficial coal mining and CBNG development. The CMGM was constructed by modifying the groundwater-flow model of Applied Hydrology Associates, Inc., and Greystone Environmental, Inc. (2002) (modifications described in detail in AECOM and Environmental Simulations, Inc., 2009). Specifically, the geographic extent of the model was substantially reduced (now a subregional model), and the number of model layers was reduced from 17 to 7. In addition, the model was transitioned from MODFLOW-96 to MODFLOW-2000 (Harbaugh and others, 2000). The model was calibrated to steady-state conditions for 1975, and then for transient conditions from 1990 to 2002. The calibrated model then was used to simulate/evaluate groundwater levels in the study area for the years 1990 and 2002, coal mine-related groundwater-level drawdowns for 2002, CBNG-related groundwater-level drawdowns and increases (mounding) for 2002, and the combined effects of coal-mine dewatering and CBNG development on groundwater levels in 2002. These simulation results were used to describe the spatial distribution of groundwater levels, including changes between 1990 and 2002 as a result of coal mining, CBNG production, or both. The investigators concluded these developmental activities from 1990 to 2002 have changed groundwater levels in some parts of the aquifer system. Groundwater-level drawdowns were large enough in some areas to alter groundwater-flow directions in parts of the aquifer system. Increased groundwater levels (mounding) from CBNG development was attributed to surficial discharge and subsequent infiltration and percolation of large volumes of water co-produced with the CBNG.

Chemical characteristics

The chemical characteristics of groundwater from the Wasatch and Fort Union aquifers and coal aquifers in the Wasatch and Fort Union Formations in the PRSB part of the NERB study area are described using environmental and produced-water samples in this section of the report. For the summary purposes of this report, groundwater-quality samples inventoried during this study originally assigned to individual members (member rank) of the Fort Union Formation were grouped together with samples assigned only to formation rank. Some evidence exists that groundwater quality in some parts of the PRSB varies between different members of the Fort Union Formation in the same general location (Gillette area) at similar depths and distance from presumed recharge along the eastern PRSB margin; these groundwater-quality differences may be attributable to different sources of the sediments composing the sandstones of different members (Wester-Wetstein and Associates, 2004b; Stetson Engineering, Inc., 2009). Groundwater quality for the Wasatch and Fort Union aquifers and coal aquifers in the Wasatch and Fort Union Formations is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix E–1).

Various aspects of the geochemical characteristics and (or) geochemical evolution of waters in aquifers (including coal aquifers) of the lower Tertiary aquifer system of Wyoming and Montana have been examined in numerous previous studies. Review of these studies is beyond the scope of this report, but interested readers are referred to the following publications: Renick, 1924; Riffenburg, 1925; Lowry and Cummings, 1966; Whitcomb and others, 1966; Hagmaier, 1971; Dahl and Hagmaier, 1974, 1976; Dockins and others, 1980a,b; Lee, 1981; Woessner and others, 1981; Slagle and others, 1985; Van Voast and Reiten, 1988; Martin and others, 1988; Rankl and Lowry, 1990; Law and others, 1991; Rice and Flores, 1991; Van Voast, 1991, 2003; Clark, 1995; Heffern and Coates, 1999; Hunter, 1999; Gorody, 1999; Rice and others, 2000, 2002, 2008; Bartos and Ogle, 2002; Frost and others, 2002, 2010; Pearson, 2002; McBeth and others, 2003a, b; Wheaton and Donato, 2004; Frost and Brinck, 2005; Jackson and Reddy, 2007a, b; Surdam and others, 2007; Brinck and others, 2008; Campbell and others, 2008; Flores and others, 2008; Wyoming State Geological Survey, 2008; Bates and others, 2011;

Quillinan, 2011; Quillinan and Frost, 2012, 2014; Lemarchand and others, 2015.

7.2.2.6.1 Wasatch aquifer

The chemical characteristics of groundwater from the Wasatch aquifer in the NERB study area are described using environmental and produced-water samples in this section of the report.

Environmental water samples

The chemical composition of groundwater from the Wasatch aquifer was characterized and the quality evaluated on the basis of environmental water samples from as many as 220 wells and one spring. Summary statistics calculated for available constituents are listed in appendix E–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram I). TDS concentrations indicated that most waters were slightly saline (101 of 220 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (96 of 220 samples, concentrations less than or equal to 999 mg/L), and the remaining waters were moderately saline (23 of 220 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–1; appendix I–1, diagram I). TDS concentrations in environmental water samples from the Wasatch aquifer ranged from 160 to 8,620 mg/L, with a median of 1,125 mg/L.

Concentrations of some characteristics and constituents measured in environmental water samples from the Wasatch aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents measured in environmental water samples at concentrations greater than health-based standards for domestic use include: radon (all 6 samples exceeded the proposed USEPA MCL of 300 pCi/L, but none exceeded the AMCL of 4,000 pCi/L), gross-alpha radioactivity (4 of 13 uncensored samples exceeded the USEPA MCL of 15 pCi/L), strontium (4 of 26 samples exceeded the USEPA HAL of 4,000 µg/L), uranium (4 of 39 samples exceeded the USEPA MCL of 30 µg/L), beryllium (2 of 31 uncensored samples exceeded the USEPA MCL of 4 µg/L), radium-226 plus radium-228 (1 of 16 uncensored samples exceeded the USEPA MCL of 5 pCi/L), selenium (3 of 54 samples exceeded the USEPA MCL of 50 µg/L), lead (2 of 46 uncensored samples exceeded the USEPA action level of 15 µg/L), molybdenum (1 of 32 samples exceeded the USEPA HAL of 40 µg/L), nitrate (3 of 107 samples exceeded the USEPA MCL of 10 mg/L), nitrate plus nitrite (2 of 81 samples exceeded the USEPA MCL of 10 mg/L), arsenic (2 of 85 samples exceeded the USEPA MCL of 10 µg/L), nickel (1 of 42 samples exceeded the USEPA HAL of 100 µg/L), cadmium (1 of 51 samples exceeded the USEPA MCL of 5 µg/L), zinc (1 of 69 samples exceeded the USEPA HAL of 2,000 µg/L), ammonia (1 of 85 samples exceeded the USEPA HAL of 30 mg/L), and fluoride (2 of 203 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations that exceeded aesthetic standards (USEPA SMCLs) for domestic use include: TDS (177 of 220 samples exceeded the SMCL of 500 mg/L), manganese (55 of 79 samples exceeded the SMCL of 50 µg/L), iron (68 of 112 samples exceeded the SMCL of 300 µg/L), sulfate (133 of 220 samples exceeded the SMCL of 250 mg/L), aluminum (3 of 25 uncensored samples exceeded the lower SMCL limit of 50 µg/L and 1 of 55 samples exceeded the upper SMCL limit of 200 µg/L), pH (3 of 215 samples below the lower SMCL limit of 6.5 and 15 of 215 samples above upper SMCL limit of 8.5), fluoride (6 of 203 samples exceeded the SMCL of 2 mg/L), zinc (1 of 69 samples exceeded the SMCL of 5,000 µg/L), and chloride (1 of 220 samples exceeded SMCL limit of 250 mg/L).

Some characteristics and constituents were measured in environmental water samples from the Wasatch aquifer in the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples from the Wasatch aquifer at concentrations greater than agricultural-use standards include: mercury (all 8 uncensored samples exceeded WDEQ Class II standard of 0.05 µg/L), sulfate (139 of 220 samples exceeded the WDEQ Class II standard of 200 mg/L), SAR (85 of 221 samples exceeded WDEQ Class II standard of 8), manganese (27 of 79 samples exceeded WDEQ Class II standard of 200 µg/L), gross-alpha radioactivity (4 of 13 samples exceeded WDEQ Class II standard of 15 pCi/L), TDS (45 of 220 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (12 of 112 samples exceeded WDEQ Class II standard of 5,000 µg/L), selenium (4 of 54 samples exceeded WDEQ Class II standard of 20 µg/L), radium-226 plus radium-228 (1 of 16 uncensored samples exceeded the WDEQ Class II standard of 5 pCi/L), boron (11 of 181 samples exceeded WDEQ Class II standard of 750 µg/L), nickel (1 of 42 samples exceeded WDEQ Class II standard of 200 µg/L), zinc (1 of 69 samples exceeded WDEQ Class II standard of 2,000 µg/L), pH (2 of 215 samples exceeded upper WDEQ Class II standard of 9), and chloride (2 of 220 samples exceeded WDEQ Class II standard of 100 mg/L). Characteristics and constituents measured at values outside the range for livestock use include: gross-alpha radioactivity (4 of 13 uncensored samples exceeded WDEQ Class III standard of 15 pCi/L), pH (3 of 215 samples below lower WDEQ Class III limit of 6.5 and

15 of 215 samples above upper WDEQ Class III limit of 8.5), radium-226 plus radium-228 (1 of 16 uncensored samples exceeded the WDEQ Class III standard of 5 pCi/L), selenium (3 of 54 samples exceeded WDEQ Class III standard of 50 µg/L), sulfate (6 of 220 samples exceeded WDEQ Class III standard of 3,000 mg/L), and TDS (4 of 220 samples exceeded WDEQ Class III standard of 5,000 mg/L).

Produced-water samples

The chemical composition of groundwater from the Wasatch aquifer also was characterized and the quality evaluated on the basis of produced-water samples from as many as 21 wells. Summary statistics calculated for available constituents are listed in appendix G–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–1, diagram A). TDS concentrations from produced-water samples indicated that the waters were slightly saline (16 of 20 samples, concentration ranging from 1,000 to 2,999 mg/L) to moderately saline (4 of 20 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix G–1; appendix K–1, diagram A). TDS concentrations in produced-water samples from the Wasatch aquifer ranged from 1,105 to 3,376 mg/L, with a median of 2,315 mg/L.

Many available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples at concentrations greater than aesthetic standards for domestic use include: TDS (all 20 samples exceeded SMCL limit of 500 mg/L), sulfate (20 of 21 samples exceeded SMCL of 250 mg/L), pH (5 of 21 samples below lower SMCL limit of 6.5), and iron (the one available sample exceeded SMCL of 300 µg/L).

Several characteristics and constituents were measured in produced-water samples from the Wasatch aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. One characteristic and one constituent were measured in produced-water samples at concentrations greater than agricultural-use standards: sulfate (20 of 21 samples exceeded WDEQ Class II standard of 200 mg/L) and TDS (12 of 20 samples exceeded WDEQ Class II standard of 2,000 mg/L). One characteristic (pH) was measured at a value that exceeded a livestock-use standard (5 of 21 samples below lower WDEQ Class III limit of 6.5).

7.2.2.6.2 Wasatch Formation coal aquifers

The chemical composition of groundwater from coal aquifers in the Wasatch Formation (Wasatch Formation coal aquifers) was characterized and the quality evaluated on the basis of water samples from as many as 8 wells. Summary statistics calculated for available constituents are listed in appendix E–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram J). TDS concentrations indicated that most waters were slightly saline (4 of 8 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (3 of 8 samples, concentrations less than or equal to 999 mg/L), and the remaining water was moderately saline (1 of 8 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–1; appendix I–1, diagram J). TDS concentrations ranged from 805 to 4,582 mg/L, with a median of 1,095 mg/L.

Concentrations of some characteristics and constituents measured in water samples from Wasatch Formation coal aquifers exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No concentrations of constituents exceeded health-based standards, but concentrations of one characteristic and two constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (all 8 samples exceeded the SMCL of 500 mg/L), iron (2 of 3 samples exceeded the SMCL of 300 µg/L), and sulfate (3 of 6 samples exceeded the SMCL of 250 mg/L).

Concentrations of some characteristics and constituents in water samples from Wasatch Formation coal aquifers exceeded State of Wyoming standards for agricultural and livestock use in the NERB. Characteristics and constituents measured in water samples from Wasatch Formation coal aquifers at concentrations greater than agricultural-use standards include: SAR (5 of 8 samples exceeded WDEQ Class II standard of 8), sulfate (3 of 6 samples exceeded the WDEQ Class II standard of 200 mg/L), iron (1 of 3 samples exceeded WDEQ Class II standard of 5,000 µg/L), and TDS (1 of 8 samples exceeded WDEQ Class II standard of 2,000 mg/L). One constituent (sulfate) was measured at a concentration outside the range for livestock use (1 of 6 samples exceeded WDEQ Class III standard of 3,000 mg/L).

7.2.2.6.3 Fort Union aquifer

The chemical characteristics of groundwater from the Fort Union aquifer in the PRSB part of the NERB study area are described using environmental and produced-water samples in this section of the report.

Environmental water samples

The chemical composition of groundwater from the Fort Union aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 233 wells and 5 springs. Summary statistics calculated for available constituents are listed in appendix E–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram K). TDS concentrations indicated that most waters were fresh (115 of 236 samples, concentrations less than or equal to 999 mg/L) to slightly saline (105 of 236 samples, concentration ranging from 1,000 to 2,999 mg/L), and remaining waters were moderately saline (16 of 236 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–1; appendix I–1, diagram K). TDS concentrations ranged from 113 to 5,480 mg/L, with a median of 1,015 mg/L.

Concentrations of some characteristics and constituents in water from the Fort Union aquifer exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents measured at concentrations greater than health-based standards include: radon (1 of 2 samples exceeded the proposed USEPA MCL of 300 pCi/L, but neither exceeded the AMCL of 4,000 pCi/L), beryllium (9 of 40 uncensored samples exceeded the USEPA MCL of 4 μg/L), radium-226 plus radium-228 (3 of 14 samples exceeded the USEPA MCL of 5 pCi/L), strontium (3 of 19 samples exceeded the USEPA HAL of 4,000 μg/L), ammonia (2 of 17 samples exceeded the USEPA HAL of 30 mg/L), lead (5 of 76 uncensored samples exceeded the USEPA action level of 15 μg/L), cadmium (3 of 66 uncensored samples exceeded the USEPA MCL of 5 μg/L), arsenic (2 of 80 samples exceeded the USEPA MCL of 10 μg/L), fluoride (4 of 191 samples exceeded the USEPA MCL of 4 mg/L), and nitrate plus nitrite (1 of 55 samples exceeded the USEPA MCL of 10 mg/L). Characteristics and constituents measured at concentrations or values that exceeded aesthetic standards (USEPA SMCLs) for domestic use include: TDS (182 of 236 samples exceeded the SMCL of 500 mg/L), sulfate (97 of 236 samples exceeded the SMCL of 250 mg/L), iron (47 of 120 samples exceeded the SMCL of 300 μg/L), manganese (23 of 72 samples exceeded the SMCL of 50 μg/L), aluminum (7 of 35 uncensored samples exceeded the lower SMCL limit of 50 μg/L and 2 of 50 samples exceeded the upper SMCL limit of 200 μg/L), fluoride (31 of 191 samples exceeded the SMCL of 2 mg/L), and pH (1 of 233 samples below the lower SMCL limit of 6.5 and 23 of 233 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in environmental water samples from the Fort Union aquifer exceeded State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations or values greater than agricultural-use standards include: mercury (the 1 water sample not censored above the standard exceeded WDEQ Class II standard of 0.05 μg/L), SAR (129 of 238 samples exceeded WDEQ Class II standard of 8), sulfate (105 of 236 samples exceeded the WDEQ Class II standard of 200 mg/L), radium-226 plus radium-228 (3 of 14 samples exceeded the WDEQ Class II standard of 5 pCi/L), TDS (36 of 236 samples exceeded WDEQ Class II standard of 2,000 mg/L), manganese (10 of 72 samples exceeded WDEQ Class II standard of 200 μg/L), iron (6 of 120 samples exceeded WDEQ Class II standard of 5,000 μg/L), boron (6 of 153 samples exceeded WDEQ Class II standard of 750 μg/L), copper (1 of 62 samples exceeded WDEQ Class II standard of 200 μg/L), cadmium (1 of 73 uncensored samples exceeded WDEQ Class II standard of 10 μg/L), arsenic (1 of 80 samples exceeded WDEQ Class II standard of 100 μg/L), and chloride (3 of 238 samples exceeded WDEQ Class II standard of 100 mg/L). Several characteristics and constituents had values outside the range for livestock-use standards: radium-226 plus radium-228 (3 of 14 samples exceeded the WDEQ Class III standard of 5 pCi/L), pH (1 of 233 samples below lower WDEQ Class III limit of 6.5 and 23 of 233 samples above upper WDEQ Class III limit of 8.5), TDS (3 of 236 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (3 of 236 samples exceeded WDEQ Class III standard of 3,000 mg/L), and boron (1 of 153 samples exceeded WDEQ Class III standard of 5,000 μg/L). One constituent (lead) was measured at a concentration equal to the livestock-use standard (1 of 86 samples equal to WDEQ Class II standard of 100 μg/L).

Produced-water samples

The chemical composition of groundwater from the Fort Union aquifer in the NERB study area also was characterized and the quality evaluated on the basis of produced-water samples from as many as 34 wells. Summary statistics calculated for available constituents are listed in appendix G–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–1, diagram B). TDS concentrations from produced-water samples were variable and indicated that most waters were fresh (14 of 34 samples, concentrations less than or equal to 999 mg/L) to slightly saline (12 of 34 samples, concentration ranging from 1,000 to 2,999 mg/L), and remaining waters were moderately saline (6 of 34 samples, concentration ranging from 3,000 to 9,999 mg/L) to briny (1 of 34 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–1; appendix K–1, diagram B). TDS concentrations in produced-water samples from the Fort Union aquifer ranged from 225 to 167,200 mg/L, with a median of 1,137 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples at concentrations or values that exceeded aesthetic standards for domestic use include: TDS (31 of 34 samples exceeded SMCL limit of 500 mg/L), iron (10 of 11 samples exceeded the SMCL of 300 μg/L), sulfate (10 of 26 samples exceeded SMCL of 250 mg/L), chloride (9 of 32 samples exceeded SMCL limit of 250 mg/L), and pH (5 of 32 samples above upper SMCL limit of 8.5).

Characteristics and constituents measured in produced-water samples that exceeded agricultural-use standards include: SAR (27 of 32 samples exceeded WDEQ Class II standard of 8), sulfate (10 of 26 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (11 of 34 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (4 of 11 samples exceeded WDEQ Class II standard of 2,000 μg/L), chloride (9 of 32 samples exceeded WDEQ Class II standard of 100 mg/L), and pH (1 of 32 samples exceeded upper WDEQ Class II standard of 9). Two characteristics and one constituent were measured at values or concentrations that exceeded livestock-use standards: pH (5 of 32 samples above upper WDEQ Class III limit of 8.5), TDS (5 of 34 samples exceeded WDEQ Class III standard of 5,000 mg/L), and chloride (2 of 32 samples exceeded WDEQ Class III standard of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 2 of 34 produced-water samples.

7.2.2.6.4 Fort Union Formation coal aquifers

The chemical composition of coal aquifers in the Fort Union Formation (Fort Union Formation coal aquifers) in the NERB study area was characterized and the quality evaluated on the basis of water samples from as many as 449 wells. The majority of water samples were collected from the variously named coal beds composing the Wyodak-Anderson coal aquifer. Summary statistics calculated for available constituents are listed in appendix E–1, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–1, diagram L). TDS concentrations indicated that most waters were slightly saline (209 of 442 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (194 of 442 samples, concentrations less than or equal to 999 mg/L), and the remaining waters were moderately saline (39 of 442 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–1; appendix I–1, diagram L). TDS concentrations for wells completed in Fort Union Formation coal aquifers ranged from 96.9 to 4,589 mg/L, with a median of 1,090 mg/L.

Concentrations of some constituents and values of some characteristics in water from wells completed in Fort Union Formation coal aquifers exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents and characteristics measured in water samples that exceeded health-based standards include: arsenic (3 of 51 samples exceeded the USEPA MCL of 10 μg/L), barium (6 of 121 samples exceeded the USEPA MCL of 2,000 μg/L), chromium (1 of 51 samples exceeded the USEPA MCL of 100 μg/L), and fluoride (1 of 132 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured in water samples that exceeded aesthetic standards (USEPA SMCLs) for domestic use include: TDS (409 of 442 samples exceeded the SMCL of 500 mg/L), iron (93 of 154 samples exceeded the SMCL of 300 μg/L), manganese (10 of 45 samples exceeded the SMCL of 50 μg/L), fluoride (9 of 132 samples exceeded the SMCL of 2 mg/L), sulfate (6 of 245 samples exceeded SMCL of 250 mg/L), pH (5 of 217 above upper SMCL limit of 8.5), and chloride (1 of 438 samples exceeded SMCL limit of 250 mg/L).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards for agricultural and livestock use. Characteristics and constituents in water samples from Fort Union Formation coal aquifers that had concentrations greater than agricultural-use standards were SAR (276 of 449 samples exceeded WDEQ Class II standard of 8), TDS (79 of 442 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (8 of 154 samples exceeded WDEQ Class II standard of 5,000 μg/L), arsenic (2 of 51 samples exceeded WDEQ Class II standard of 100 μg/L), sulfate (7 of 245 samples exceeded the WDEQ Class II standard of 200 mg/L), chromium (1 of 51 samples exceeded WDEQ Class II standard of 100 μg/L), chloride (4 of 438 samples exceeded WDEQ Class II standard of 100 mg/L), and pH (1 of 217 samples exceeded the upper WDEQ Class II standard of 9). One characteristic and two constituents were measured at concentrations or values outside the range for livestock use: arsenic (2 of 51 samples exceeded WDEQ Class III standard of 200 μg/L), pH (5 of 217 samples above upper WDEQ Class III limit of 8.5), and chromium (1 of 51 samples exceeded WDEQ Class III standard of 50 μg/L).

7.2.2.7 Fort Union aquifer (Wind River structural basin)

The physical and chemical characteristics of the Fort Union aquifer in the part of the Wind River structural basin (WRSB) within the NERB study are described in this section of the report.

Physical characteristics

The Fort Union aquifer in the part of the WRSB within the NERB study area consists of the water-saturated and permeable parts of the Fort Union Formation. The Fort Union Formation in the WRSB was classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). The Fort Union Formation consists of an interbedded sequence of coarse-grained rocks (sandstone and conglomerate) and intervening fine-grained mudrocks (claystone, shale, carbonaceous shale, siltstone) deposited in fluvial, paludal, and lacustrine environments (Keefer, 1961a, b, 1965, 1969). The saturated and permeable sandstone and conglomerate beds and lenses in the formation contain the aquifers (Whitcomb and Lowry, 1968; Richter, 1981; Flores and others, 1993). Maximum thickness of the Fort Union Formation in the WRSB varies substantially and ranges from hundreds to thousands of feet (Keefer, 1961a,b, 1965, 1969). In the WRSB, the Fort Union aquifer is overlain by the Indian Meadows confining unit composed of the Eocene-age Indian Meadows Formation and underlain by the Lance aquifer composed of the Late Cretaceous-age Lance Formation (Bartos and others, 2012, plate II).

Groundwater in the Fort Union aquifer is mostly under confined conditions, but unconfined (water-table) conditions are likely at shallow depths where the Fort Union Formation outcrops (Whitcomb and Lowry, 1968; Richter, 1981). Permeability of sandstone beds composing the Fort Union aquifer is primarily intergranular, but fractures in structurally deformed areas may enhance aquifer permeability (Richter, 1981). Few groundwater wells are installed in the Fort Union aquifer in the WRSB, and most are for stock use (Taucher and others, 2012). Relatively low yields, variable groundwater quality, variable hydrogeologic characteristics, and limited geographic extent preclude much aquifer development in the WRSB (Taucher and others, 2012). Few hydrogeologic data describing the physical characteristics of the Fort Union aquifer in the WRSB part of the NERB were located and inventoried as part of this study, but available data are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Fort Union aquifer in the small part of the WRSB within the NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Fort Union aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices F and H).

Environmental water samples

The chemical composition of groundwater from the Fort Union aquifer in the WRSB was characterized and the quality evaluated on the basis of environmental water samples from as many as 4 wells and one spring. Summary statistics calculated for available constituents are listed in appendix F. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix J, diagram A). TDS concentrations indicated that waters were fresh (3 of 5 samples, TDS concentrations less than or equal to 999 mg/L) to slightly saline (2 of 5 samples, TDS concentrations ranging from 1,000 to 2,999 mg/L) (appendix F; appendix J, diagram A). TDS concentrations in waters from the wells ranged from 400 to 1,940 mg/L, with a median of 767 mg/L.

Concentrations of some characteristics and constituents measured in environmental water samples from the Fort Union aquifer exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured in an environmental water sample at a concentration greater than a health-based standard [1 of 2 samples (sample from spring) exceeded the USEPA MCL of 4 mg/L]. Characteristics and constituents measured in environmental water samples at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (4 of 5 samples exceeded the SMCL of 500 mg/L), sulfate [4 samples (samples from wells) exceeded the SMCL of 250 mg/L], fluoride [1 of 2 samples (sample from spring) exceeded the SMCL of 2 mg/L], and pH [1 of 5 samples (sample from spring) above upper SMCL limit of 8.5].

Several characteristics and constituents were measured in environmental water samples from the Fort Union aquifer in the WRSB at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate [4 samples

(samples from wells) exceeded the WDEQ Class II standard of 200 mg/L], SAR [1 of 5 samples (sample from spring) exceeded WDEQ Class II standard of 8]. Only one characteristic (pH) was measured at a value outside the range for livestock use [1 of 5 samples (sample from spring) above upper WDEQ Class III limit of 8.5].

Produced-water samples

The chemical composition of groundwater from the Fort Union aquifer in the WRSB also was characterized and the quality evaluated on the basis of 31 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram B). TDS concentrations from produced-water samples were variable and indicated that many waters were moderately saline (16 of 31 samples, concentrations ranging from 3,000 to 9,999 mg/L) and slightly saline (11 of 31 samples, concentration ranging from 1,000 to 2,999 mg/L), and the remaining waters were very saline (3 of 31 samples, concentrations ranging from 10,000 to 34,999 mg/L) to fresh (1 of 31 samples, concentrations less than or equal to 999 mg/L) (appendix H; appendix L, diagram B). TDS concentrations in produced-water samples from the Fort Union aquifer ranged from 270 to 15,900 mg/L, with a median of 3,720 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples that exceeded aesthetic standards (USEPA SMCLs) for domestic use include: TDS (30 of 31 samples exceeded SMCL limit of 500 mg/L), chloride (25 of 31 samples exceeded SMCL limit of 250 mg/L), iron (6 samples exceeded SMCL of 300 µg/L), sulfate (8 of 29 samples exceeded SMCL of 250 mg/L), and pH (2 of 31 samples below lower SMCL limit of 6.5 and 4 of 31 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water water samples from the Fort Union aquifer in the WRSB at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples that exceeded agricultural-use standards include: SAR (30 of 31 samples exceeded WDEQ Class II standard of 8), chloride (28 of 31 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (27 of 31 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (4 of 6 samples exceeded WDEQ Class II standard of 5,000 µg/L), and sulfate (8 of 29 samples exceeded WDEQ Class II standard of 200 mg/L). Two characteristics and one constituent were measured at concentrations or values that exceeded livestock-use standards: TDS (11 of 31 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (7 of 31 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (2 of 31 samples below lower WDEQ Class III limit of 6.5 and 4 of 31 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 3 of 31 produced-water samples.

7.3 MESOZOIC HYDROGEOLOGIC UNITS

Mesozoic hydrogeologic units in the NERB study area consisting of sedimentary rocks ranging from Cretaceous to Triassic in age are identified and described in this section of the report. Some sedimentary rocks of Permian age also are discussed in this section of the report because they are part of a regional hydrogeologic unit also composed of rocks of Triassic and Jurassic age. Mesozoic-age lithostratigraphic units composed of sedimentary rocks are shown in relation to hydrogeologic units on fig. 7-2 and plate 2.

Upper Cretaceous hydrogeologic units

Upper Cretaceous hydrogeologic units composed of Late Cretaceous age sedimentary rocks in the NERB study area are identified, and associated physical and chemical characteristics described, in this section of the report. Hydrogeologic units composing the regionally extensive Upper Cretaceous aquifer system in the Northern Great Plains regional aquifer system are identified and described first, and then Upper Cretaceous hydrogeologic units not associated with the aquifer system used in the WRSB part of the NERB study area are identified and described.

7.3.1 Upper Cretaceous aquifer system (Lance Formation and Fox Hills Sandstone in the Powder River Basin)

Hydrogeologic units composing the Upper Cretaceous aquifer system in the NERB study area are identified, and the physical and chemical characteristics described, in this section of the report.

Physical characteristics

The large, geographically extensive Upper Cretaceous aquifer system coincides with the boundary of the PRSB in Wyoming and Montana and includes a large part of the NERB study area (fig. 7-7; plate 2). The regional aquifer system consists of the Late Cretaceous-age Lance Formation and Fox Hills Sandstone grouped into different hydrogeologic units, generally named after their respective lithostratigraphic units (figs. 7-2, 7-7, 7-8). Both the Lance Formation and Fox Hills Sandstone are present throughout the PRSB, but outcrops are limited to the perimeter of the basin (fig. 7-7; plate 1). The formations crop out in a very narrow band on the basin margin along the Bighorn Mountains and southernmost part of the basin, and over a larger area on the southwestern, southeastern, and northeastern basin margins along the other surrounding uplifts (Laramie Mountains, Hartville uplift, Casper arch, and Black Hills).

In the part of the PRSB within Montana, the Lance Formation is known as the stratigraphically equivalent Hell Creek Formation. The name "Hell Creek" commonly is used instead of "Lance" in regional USGS studies describing the hydrogeologic unit throughout the full geographic extent in the PRSB in both states. Because of the emphasis on the Wyoming part of the PRSB in this study, and because most studies within Wyoming replace the name "Hell Creek" with the name "Lance" for essentially the same lithostratigraphic unit present in both states, only "Lance" will be used hereinafter in text and figures and on plates.

Deposited mainly in fluvial environments during and following the final regression of the Western Interior Seaway, the Lance Formation is the uppermost (youngest) Cretaceous lithostratigraphic unit in the PRSB and NERB study area (fig. 7-2); the formation marks the end of marine deposition (Gill and Cobban, 1973). The Lance Formation consists primarily of sequences of sandstone, sandy shale, claystone/mudstone, shale (commonly carbonaceous), and thin beds of locally occurring coal (Robinson and others, 1964; Gill and Cobban, 1973; Gill and Burkholder, 1979; Lewis and Hotchkiss, 1981; Connor, 1992; Merewether, 1996, and references therein). Connor (1992) estimated lenticular channel sandstones 20 ft or more in thickness compose about 30 percent of the Lance Formation in the PRSB, and thinner sandstone beds and fine-grained interfluvial rocks such as shale and claystone compose the remaining 70 percent. Sandstone beds are lenticular, very fine- to coarse-grained, generally friable, very thin- to very thick-bedded or massive, and crossbedded in places. Lenticular sandstone beds range from isolated bodies to stacked sequences as much as 300-ft thick (Connor, 1992).

The nonmarine Lance Formation is conformably overlain by the nonmarine Paleocene-age Tullock Member of the Fort Union Formation and conformably overlies and intertongues with the marine Fox Hills Sandstone (fig. 7-2; Gill and Cobban, 1973; Connor, 1992). Determining the contact between the Lance Formation and the overlying Tullock Member of the Fort Union Formation is difficult at outcrops and on borehole logs (Lowry, 1972, 1973; Connor, 1992; Brown, 1993, and references therein; Merewether, 1996, and references therein). Similarly, the contact between the Lance Formation and Fox Hills Sandstone also is difficult to determine, especially in the subsurface using only geophysical logs. Connor (1992, p. I2) noted that the transition from the marine environment of the Fox Hills Sandstone to the nonmarine environment of the Lance Formation "is rarely abrupt, and there is commonly an intertonguing interval that appears to be several hundred feet thick." In addition, it is difficult to determine the contact consistently throughout the entire structural basin (Connor, 1992). Consequently, because the contact with the overlying Tullock Member of the Fort Union Formation and the underlying Fox Hills Sandstone is difficult to determine, thickness estimates of the Lance Formation vary among studies. Rapp (1953) estimated thickness to be as much as 3,000 ft in southern Converse County. Horn (1955) estimated thickness to be about 2,400 ft in southern Johnson County. Mapel (1959) estimated thickness to be about 2,000 ft near Buffalo. Rich (1962) estimated a thickness of 1,755 ft in southern Natrona County. Robinson and others (1964) estimated thickness to range from about 500 ft in northeastern Campbell County to about 1,600 ft in northern Weston County. Keefer (1965) estimated Lance Formation thickness to range from 1,600 ft in northern Weston County to 6,000 ft in northwestern Natrona County. Whitcomb (1965) estimated thickness to be about 2,500 ft in Niobrara County.

Deposited in nearshore marine and deltaic environments, the Fox Hills Sandstone is a transitional sequence that was deposited during the final regression of the Cretaceous Interior Sea (Gill and Cobban, 1973). The Fox Hills Sandstone consists of interbedded very fine- to medium-grained sandstone, with much lesser amounts of siltstone, sandy shale, shale, and carbonaceous shale (Robinson and others, 1964; Gill and Cobban, 1973; Gill and Burkholder, 1979; Lewis and Hotchkiss, 1981; Connor, 1992; Merewether, 1996, and references therein). In most of the PRSB, the Fox Hills Sandstone conformably overlies and is gradational with either the Pierre or Lewis Shales (Merewether, 1996, and references therein). Robinson and others (1964) estimated thickness of the Fox Hills Sandstone to range from about 125 to 200 ft in Crook and Weston Counties. Whitcomb (1965) estimated thickness to be about 700 ft in the southwestern part of the PRSB. Measured thickness of the Fox Hills Sandstone using outcrops ranges from 38 to 67 ft in Sheridan and Johnson Counties, and from 300 to 400 ft in Niobrara and Converse Counties (Stanton, 1910; Dobbin and Reeside, 1929; Dorf, 1942; Merewether and others, 1977a, b, c, d; Gill and Burkholder, 1979).

Because of difficulty determining the contact consistently between the Lance Formation and Fox Hills Sandstone, two studies combined the formations to create an isopach (thickness) map for the PRSB in both Wyoming and Montana (Curry, 1971, fig. 6; Connor, 1992, plate 5). Both maps show consistent southward thickening of the combined formations from north to south, as well as little to no thickness change from east to west. The map prepared by Connor (1992, plate 5) shows southward thickening in the Wyoming part of the PRSB ranging from about 900 ft in the north to more than 3,300 ft in the south.

Individual aquifers in the Lance Formation and Fox Hills Sandstone in the PRSB consist of sandstone beds where water-saturated and sufficiently permeable ("sandstone aquifers") to produce usable quantities of water (Littleton, 1950; Morris, 1956; Dana, 1962; Johnson, 1962; Whitcomb and Morris, 1964; Whitcomb, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Lowry, 1972, 1973; Groundwater Subgroup, 1974; Hodson and others, 1973, sheet 3, and references therein; Feathers and others, 1981; Lewis and Hotchkiss, 1981; Stock, 1981; Western Water Consultants, Inc., 1983). Sandstone aquifers in both formations are used as sources of water, most commonly for livestock and domestic purposes in and near outcrop areas, but also less commonly where water quantity/quality are sufficient for industrial and public-supply purposes (Feathers and others, 1981; Wyoming Water Development Commission, 1985; Wyoming State Engineer's Office, 1995; HKM Engineering, Inc., and others, 2002a, b, and references therein). Several municipal water systems located in the PRSB utilize groundwater from the Lance Formation and (or) Fox Hills Sandstone as a source of water for all or part of their public supply, including the cities of Gillette, Glenrock, Edgerton, and Moorcroft (HKM Engineering, Inc., and others, 2002a, b, and references therein). Unconfined conditions in both formations may occur in or near outcrop areas at shallow depths, but confined conditions are more common because of aquifer burial. In some areas, artesian pressure is sufficient to cause groundwater wells completed in the aquifers to flow at the surface.

Hydrogeologic data describing the Lance Formation (aquifer) and Fox Hills Sandstone (aquifer) in the NERB, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3. Hydraulic characteristics determined from wells completed in both formations, including well yields, are highly variable (plate 3). Although well yields inventoried for this study were as large as 300 gal/min for wells completed in the Lance Formation, and as large as 5,000 gal/min for wells completed in the Fox Hills Sandstone, inventoried yields were low for most wells completed either formation, as indicated by a median well yield of 10 gal/min for wells completed in either formation (plate 3). Large variability of reported hydraulic characteristics reflects variable characteristics of the sandstone beds containing the aquifers and differing well construction. As described previously, sandstone beds, and thus, aquifers, in both formations vary widely in geometry, are mostly lenticular and laterally and vertically discontinuous, especially in the Lance Formation. In addition, well construction also affects reported hydraulic characteristics. Low well yields in both formations may not be representative of the maximum yield possible from both formations because the vast majority of inventoried wells are domestic and stock wells completed in and near the outcrop areas. These types of groundwater wells generally are shallow and are not constructed to penetrate all of the sandstone beds throughout the entire saturated thickness of the formation. Well yields sufficiently large for industrial and public-supply use have been obtained from the Fox Hills Sandstone by locating deeply buried thick sandstone aquifers and by penetrating multiple sandstone aquifers within the formation (Hodson and others, 1973, and references therein; Feathers and others, 1981; Wyoming Water Development Commission, 1985; HKM Engineering, Inc., and others, 2002a, b, and references therein).

Several studies noted that although individual sandstone aquifers in the Lance Formation and the Fox Hills Sandstone have limited areal extent and are considered aquifers at the local scale, they are sufficient in number, and hydraulic connection between them sufficient that the lithostratigraphic units as a whole can be considered to be regional (basinwide) hydrogeologic units in a broader aquifer system present throughout the PRSB in Wyoming and Montana (fig. 7-2) (Feathers and others, 1981; Lewis and Hotchkiss, 1981; Downey, 1986; Hotchkiss and Levings, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995; Whitehead, 1996; Thamke and others, 2014). These regional hydrogeologic units were grouped into an unnamed aquifer system (Lewis and Hotchkiss, 1981; Hotchkiss and Levings, 1986), the Fox Hills/Lance aquifer system (Feathers and others, 1981), the Upper Cretaceous aquifer/aquifers/aquifer system (Downey, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995; Whitehead, 1996), or the Upper Cretaceous aquifer system (Thamke and others,

2014) (fig. 7-2). Because of emphasis on older and deeper aquifers/aquifer systems, several of these studies also included all of the overlying Wasatch and Fort Union Formations as part of their definition of the Upper Cretaceous aquifer system (Downey, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995). All of these studies built upon the data and interpretation of Lewis and Hotchkiss (1981). Using numerous geophysical logs, Lewis and Hotchkiss (1981) mapped the horizontal and vertical sandstone content for the entire thickness of both the Lance Formation and Fox Hills Sandstone throughout the PRSB in both Wyoming and Montana. Subsequently, the investigators used the resulting sandstone content maps to identify and name regional hydrogeologic units composed of all or parts of the two formations. Feathers and others (1981) included the overlying Tullock Member of the Fort Union Formation as part of the aquifer system (fig. 7-2), apparently based at least in part on experiences with water well development near the Hilight oilfield where local hydraulic connection between the three lithostratigraphic units was documented by Lowry (1972, 1973). Many studies in Wyoming use "Lance/Fox Hills aquifer" to identify the aquifer system composed of all or parts of the Lance Formation and Fox Hills Sandstone, but many of them are simply grouping the aquifers in both formations together without inclusion of the overlying Tullock Member of the Fort Union Formation. This study uses the aquifer system nomenclature as originally defined by Lewis and Hotchkiss (1981), and subsequently refined by Hotchkiss and Levings (1986) and Thamke and others (2014). To reflect current USGS usage (Thamke and others, 2014; Long and others, 2014) and to unify nomenclature, "Upper Cretaceous aquifer system" is used herein to name the aquifer system with one modification—replacement of "Hell Creek" with "Lance" to reflect emphasis on and widespread usage in Wyoming (fig. 7-2).

From youngest (shallowest) to oldest (deepest), the Upper Cretaceous aquifer system consists of the Upper Lance hydrogeologic unit, lower Lance aquifer, and the Fox Hills aquifer (figs. 7-2, 7-8; Lewis and Hotchkiss, 1981; Hotchkiss and Levings, 1986; Thamke and others, 2014). The upper Lance hydrogeologic unit consists of the upper part of the Lance Formation in Wyoming and the stratigraphically equivalent upper part of the Hell Creek Formation in Montana (figs. 7-2, 7-8). Lithology in the underlying lower Lance aquifer is very similar, so the upper Lance hydrogeologic unit is defined where the relative percentage of sandstone is generally smaller than that of the underlying lower Lance aquifer. The "upper Lance" is defined as a hydrogeologic unit because that part of the formation may regionally act as a confining unit in some areas and as an aquifer in other areas because of spatially variable lithology. The Fox Hills aquifer consists of the Fox Hills Sandstone in Wyoming and Montana (figs. 7-2, 7-8). The lower Lance and Fox Hills aquifers commonly are combined and referred to as the Lance-Fox Hills aquifer or lower Lance-Fox Hills aquifer. Present throughout all of the PRSB (figs. 7-2, 7-8), the Fox Hills aquifer is the deepest hydrogeologic unit of the Upper Cretaceous aquifer system. The Upper Cretaceous aquifer system is underlain and confined from below by the Upper Cretaceous confining unit, consisting primarily of thousands of feet of marine shale that hydraulically separates the aquifer system and the overlying lower Tertiary aquifer system from all stratigraphically older aquifers/aquifer systems in the PRSB. For the entire geographic extent in Wyoming and Montana, thickness of the Upper Cretaceous aquifer system is as much as 5,070 ft, and estimated volume is 938 trillion ft^3 (Thamke and others, 2014, table 5).

Recharge to the Upper Cretaceous aquifer system is provided primarily by direct infiltration and percolation of precipitation (snowmelt and rain), runoff from rain and snowmelt, ephemeral and perennial streamflow losses on formation outcrops, and interformational leakage from overlying strata (Feathers and others, 1981; Western Water Consultants, Inc., 1983; Hotchkiss and Levings, 1986; Aurand, 2013; Bednar, 2013; Long and others, 2014). Recharge to the aquifer system also occurs in areas where the Lance Formation and Fox Hills Sandstone are overlain by water-saturated alluvium (Western Water Consultants, Inc., 1983). Discharge from the aquifer system is naturally by vertical movement to adjacent hydrogeologic units (interformational flow), base flow to streams (in or near outcrop areas), and anthropogenically by withdrawals from various types of groundwater wells (Feathers and others, 1981; Stock, 1981; Western Water Consultants, Inc., 1983; Hotchkiss and Levings, 1986; Aurand, 2013; Bednar, 2013; Long and others, 2014). A basinwide (PRSB in both Wyoming and Montana) water budget for the combined Upper Cretaceous and lower Tertiary aquifer systems constructed as part of a regional USGS study (Aurand, 2013; Bednar, 2013; Long and others, 2014) is described in the "Lower Tertiary aquifer system" section of this report.

A generalized regional potentiometric surface of the Upper Cretaceous aquifer system constructed originally by Hotchkiss and Levings (1986) and subsequently modified by Thamke and others (2014) is reproduced herein as fig. 7-14. The potentiometric surface for the Upper Cretaceous aquifer system represents the average generalized potentiometric surface for the lower Lance-Fox Hills aquifer during 1975-80. The shape of the potentiometric surface of the Upper Cretaceous aquifer system (fig. 7-14) generally resembles that of the overlying Tullock aquifer (fig. 7-12), the lowermost hydrogeologic unit of the overlying lower Tertiary aquifer system. The general movement of groundwater in the Upper Cretaceous aquifer system as indicated by the lower Lance-Fox Hills aquifer is northward in the PRSB. The potentiometric surface of the Tullock aquifer is substantially higher than that of the lower Lance-Fox Hills aquifer in the Upper Cretaceous aquifer system, indicating the upper Lance hydrogeologic unit provides hydraulic separation from the lowermost aquifer of the overlying lower Tertiary aquifer system, at least in some areas. Potentiometric surfaces for the Tullock aquifer and the lower Lance-Fox Hills aquifer are similar in the middle part of the PRSB. In the northern part of the PRSB in the NERB study area in Wyoming, groundwater in the Tullock aquifer flows towards the Tongue River which is not apparent in the lower Lance-Fox Hills aquifer of the Upper Cretaceous aquifer system (figs. 7-12, 7-14).

Chemical characteristics

The chemical characteristics of groundwater from the Lance and Fox Hills aquifers in the Upper Cretaceous aquifer system in the NERB study area excluding the WRSB are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Lance and Fox Hills aquifers is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

Lance aquifer

The chemical characteristics of groundwater from the Lance aquifer in the PRSB part of the NERB are described using environmental and produced-water samples in this section of the report. Available groundwater-quality data were assigned only to lithostratigraphic unit (Lance Formation), so groundwater-quality data from the Lance Formation are assigned to the Lance aquifer and are not separated into the "upper" and "lower" Lance hydrogeologic units of the Upper Cretaceous aquifer system.

Environmental water samples

The chemical composition of groundwater from the Lance aquifer in the NERB was characterized and the quality evaluated on the basis of environmental water samples from as many as 48 wells. Summary statistics calculated for available constituents are listed in appendix E–2, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram A). TDS concentrations indicated that most waters were to fresh (26 of 47 samples, concentrations less than or equal to 999 mg/L) to slightly saline (20 of 47 samples, concentration ranging from 1,000 to 2,999 mg/L), and remaining water was moderately saline (1 of 47 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–2; appendix I–2, diagram A). TDS concentrations ranged from 244 to 3,060 mg/L, with a median of 946 mg/L.

Concentrations of some characteristics and constituents in water from Lance aquifer in the NERB exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents measured at concentrations greater than health-based standards include: uranium (2 of 6 samples exceeded the USEPA MCL of 30 mg/L), strontium (1 of 8 samples exceeded the USEPA HAL of 4,000 μg/L), and fluoride (2 of 47 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (44 of 47 samples exceeded the SMCL of 500 mg/L), sulfate (27 of 48 samples exceeded the SMCL of 250 mg/L), aluminum (1 of 2 uncensored samples exceeded the lower SMCL limit of 50 μg/L), fluoride (9 of 47 samples exceeded the SMCL of 2 mg/L), manganese (2 of 11 samples exceeded the SMCL of 50 μg/L), pH (7 of 46 samples above the upper SMCL limit of 8.5), and iron (2 of 14 samples exceeded the SMCL of 300 μg/L).

Some characteristics and constituents were measured in environmental water samples from the Lance aquifer in the NERB at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: mercury (both of the uncensored samples exceeded WDEQ Class II standard of 0.05 μg/L), SAR (32 of 48 samples exceeded WDEQ Class II standard of 8), sulfate (30 of 48 samples exceeded the WDEQ Class II standard of 200 mg/L), manganese (1 of 11 samples exceeded WDEQ Class II standard of 200 μg/L), TDS (4 of 47 samples exceeded WDEQ Class II standard of 2,000 mg/L), boron (1 of 44 samples exceeded WDEQ Class II standard of 750 μg/L), and chloride (1 of 48 samples exceeded WDEQ Class II standard of 100 mg/L). One characteristic (pH) was measured at values outside the range for livestock use (7 of 46 samples above upper WDEQ Class III limit of 8.5).

Produced-water samples

The chemical composition of groundwater from the Lance aquifer in the PRSB part of the NERB also was

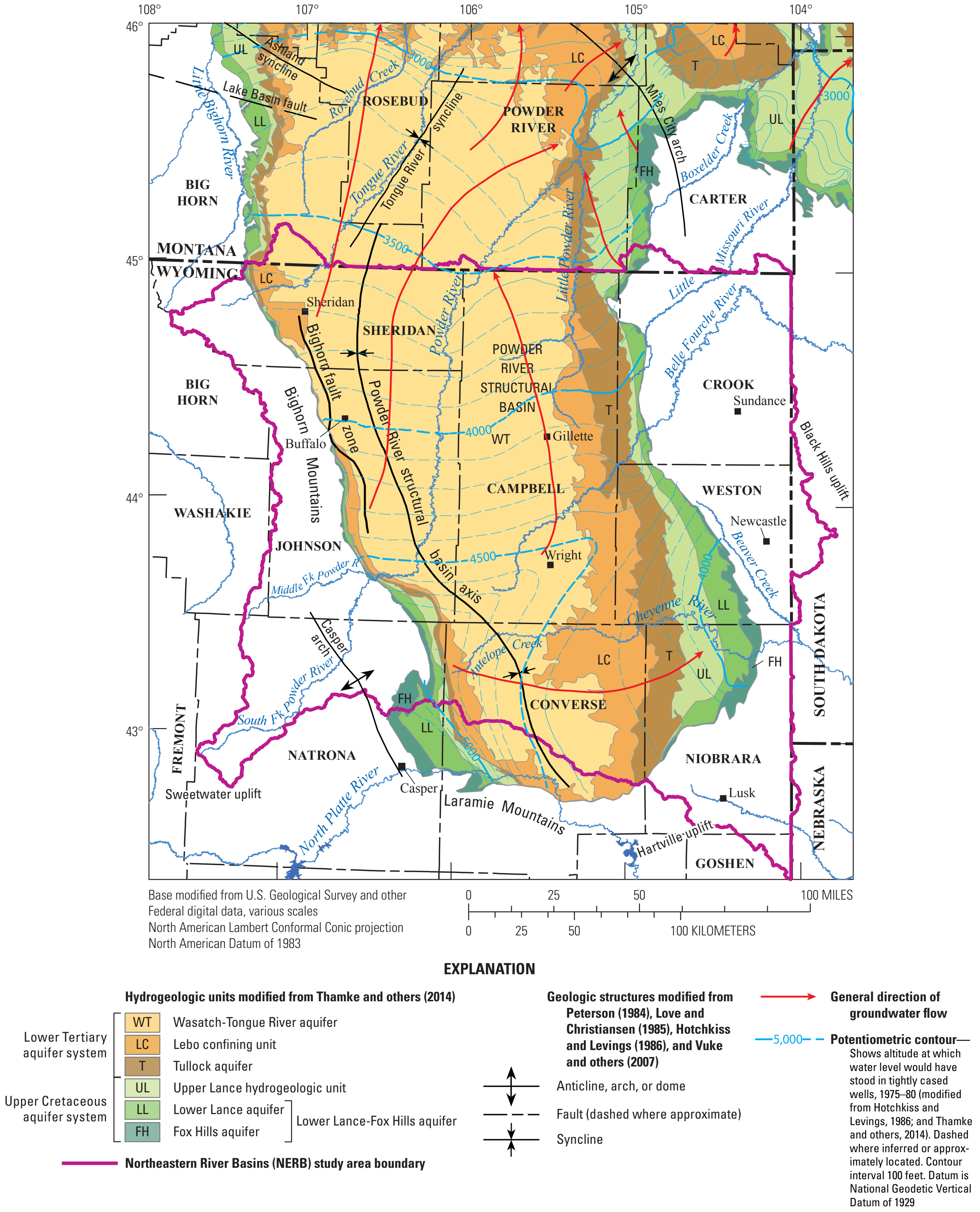


Figure 7-14. Potentiometric surface of the lower Lance-Fox Hills aquifer of the Upper Cretaceous aquifer system in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

characterized and the quality evaluated on the basis of 57 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram A). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (27 of 57 samples, concentrations ranging from 3,000 to 9,999 mg/L) to slightly saline (25 of 57 samples, concentration ranging from 1,000 to 2,999 mg/L), and remaining waters were briny (4 of 57 samples, concentrations greater than or equal to 35,000 mg/L) to very saline (1 of 57 samples, concentrations ranging from 10,000 to 34,999 mg/L) (appendix G–2; appendix K–2, diagram A). TDS concentrations ranged from 1,002 to 47,910 mg/L, with a median of 3,280 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 57 samples exceeded SMCL limit of 500 mg/L), chloride (51 of 57 samples exceeded SMCL limit of 250 mg/L), iron (9 of 16 samples exceeded the SMCL of 300 µg/L), sulfate (13 of 49 samples exceeded SMCL of 250 mg/L), and pH (2 of 56 samples below lower SMCL limit of 6.5 and 8 of 56 samples above upper SMCL limit of 8.5).

Some characteristics and constituents were measured in produced-water samples from the Lance aquifer in the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 56 samples exceeded WDEQ Class II standard of 8), chloride (51 of 57 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (37 of 57 samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (16 of 49 samples exceeded WDEQ Class II standard of 200 mg/L), iron (4 of 16 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (1 of 56 samples below lower WDEQ Class II limit of 4.5). Characteristics and constituents measured in produced-water samples at concentrations greater than livestock-use standards include: TDS (16 of 57 samples exceeded WDEQ Class III standard of 5,000 mg/L), pH (2 of 56 samples below lower WDEQ Class III limit of 6.5 and 8 of 56 samples above upper WDEQ Class III limit of 8.5), chloride (6 of 57 samples exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate (4 of 49 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 5 of 57 produced-water samples.

Fox Hills aquifer

The chemical characteristics of groundwater from the Fox Hills aquifer in the PRSB part of the NERB are described using environmental and produced-water samples in this section of the report.

Environmental water samples

The chemical composition of groundwater from the Fox Hills aquifer in the NERB was characterized and the quality evaluated on the basis of environmental water samples from as many as 21 wells. Summary statistics calculated for available constituents are listed in appendix E–2, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram B). TDS concentrations indicated that most waters were slightly saline (10 of 21 samples, concentrations ranging from 1,000 to 2,999 mg/L) to fresh (8 of 21 samples, concentrations less than or equal to 999 mg/L), and remaining waters were moderately saline (3 of 21 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–2; appendix I–2, diagram B). TDS concentrations ranged from 28.0 to 3,520 mg/L, with a median of 1,170 mg/L.

Concentrations of some characteristics and constituents in water from the Fox Hills aquifer exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured at concentrations greater than a health-based standard (4 of 21 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured in environmental water samples at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (20 of 21 samples exceeded the SMCL of 500 mg/L), sulfate (15 of 21 samples exceeded the SMCL of 250 mg/L), iron (1 of 3 samples exceeded the SMCL of 300 µg/L), fluoride (5 of 21 samples exceeded the SMCL of 2 mg/L), and pH (4 of 21 samples above upper SMCL limit of 8.5).

Some characteristics and constituents were measured in environmental water samples from the Fox Hills aquifer in the NERB at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: SAR (16 of 21 samples exceeded WDEQ Class II standard of 8), sulfate (16 of 21 samples exceeded the WDEQ Class II standard of

200 mg/L), TDS (4 of 21 samples exceeded WDEQ Class II standard of 2,000 mg/L), boron (1 of 16 samples exceeded WDEQ Class II standard of 750 µg/L), and pH (1 of 21 samples exceeded upper WDEQ Class II standard of 9). One characteristic (pH) was measured at values outside the range for livestock-use standards (4 of 21 samples above upper WDEQ Class III limit of 8.5).

Produced-water samples

The chemical composition of groundwater from the Fox Hills aquifer in the NERB was also characterized and the quality evaluated on the basis of as many as 79 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram B). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (41 of 78 samples, concentration ranging from 1,000 to 2,999 mg/L) and remaining waters were fresh (26 of 78 samples, concentrations less than or equal to 999 mg/L) to moderately saline (11 of 78 samples, concentrations ranging from 3,000 to 9,999 mg/L) (appendix G–2; appendix K–2, diagram B). TDS concentrations ranged from 325 to 6,758 mg/L, with a median of 1,234 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One produced-water sample included a constituent that could be compared to health-based standards: fluoride (the one sample analyzed for this constituent exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: fluoride (the one sample analyzed for this constituent exceeded the SMCL of 2 mg/L), TDS (77 of 78 samples exceeded SMCL limit of 500 mg/L), iron (17 of 23 samples exceeded the SMCL of 300 µg/L), sulfate (21 of 73 samples exceeded SMCL of 250 mg/L), chloride (18 of 78 samples exceeded SMCL limit of 250 mg/L), and pH (14 of 68 samples above upper SMCL limit of 8.5).

Some characteristics and constituents were measured in produced-water samples from the Fox Hills aquifer in the NERB at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (70 of 74 samples exceeded WDEQ Class II standard of 8), chloride (30 of 78 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (27 of 73 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (19 of 78 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (2 of 23 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (1 of 68 samples above upper WDEQ Class II limit of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: pH (14 of 68 samples above upper WDEQ Class III limit of 8.5), TDS (2 of 78 samples exceeded WDEQ Class III standard of 5,000 mg/L), and chloride (2 of 78 samples exceeded WDEQ Class III standard of 2,000 mg/L).

7.3.2 Upper Cretaceous confining unit (Lewis, Pierre, Mesaverde, Cody, Steele, Niobrara, Carlile, Frontier, Greenhorn, and Mowry hydrogeologic units in the Powder River Basin)

The physical and chemical characteristics of the hydrogeologic units composing the Upper Cretaceous confining unit are discussed in this section of the report.

Physical characteristics

Late-Cretaceous age lithostratigraphic units underlying the Upper Cretaceous aquifer system collectively compose a thick, geographically extensive regional confining unit present throughout much of the NERB study area (Feathers and others, 1981, fig. II-4; Fitzwater, 1981; Downey, 1986; Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988; Busby and others, 1995; Whitehead, 1996; Thamke and others, 2014). Identified herein as the Upper Cretaceous confining unit, the regional confining unit separates and hydraulically isolates the overlying Upper Cretaceous aquifer system and all overlying Cenozoic aquifers/aquifer systems from all stratigraphically older aquifers/aquifer systems (fig. 7-2). Within the NERB study area, lithostratigraphic units composing the confining unit underlie most of the PRSB and the flanks of the adjacent structurally uplifted areas, although units present differ by geographic area (fig. 7-2; plates 1, 2). Individual lithostratigraphic units and (or) parts of the units composing the Upper Cretaceous confining unit laterally grade and intertongue in outcrops and in the subsurface, chronicling the multiple westward transgressions and eastward regressions of the north-trending epeiric sea in the Western Interior Seaway (Merewether and others, 1977a, b, c; Fox, 1993a, b, c, d; Merewether, 1996, and references therein). Rocks composing the confining unit were deposited in continental, near-shore marine, and offshore-marine environments on the west side of the Western Interior Seaway. Sediments composing much of the continental and near-shore marine rocks were eroded from areas of central and northwestern Wyoming, eastern Idaho, and western Montana. Dark, clayey low-permeability shale with lesser amounts of siltstone and interbedded sandstone deposited during transgressions of the Late Cretaceous inland sea compose most of the confining unit, although minor volumes of sandy shale, limestone, marl, mudstone, and bentonite beds are present in several of the lithostratigraphic units (Merewether, 1996, and references therein; Anna, 2010, and references therein). Sandstone beds in several of the lithostratigraphic units yield water and (or) petroleum, and the petroleum-saturated beds (reservoirs) are developed extensively in parts of the NERB study area (Dolton and others, 1990; Hansley and Whitney, 1990; Nuccio, 1990; Higley, 1992; Merewether, 1996; Anna, 2010, and references therein).

Stratigraphy of the various lithostratigraphic units composing the Upper Cretaceous confining unit is very complex, and the nomenclature and stratigraphic and geographic boundaries of individual units has been repeatedly revised over time (for example, Merewether, 1996, and references therein). In the eastern PRSB, Black Hills uplift, and adjacent areas, the Upper Cretaceous confining unit consists of, from stratigraphically youngest to oldest, the Pierre Shale, Niobrara Formation, Carlile Shale, Greenhorn Formation, Belle Fourche Shale, and the Mowry Shale. In the western PRSB, eastern flank of the Bighorn Mountains, and Casper arch area, the Upper Cretaceous confining unit consists of, from stratigraphically youngest to oldest, the Meeteetse Formation, Bearpaw and Lewis Shales, Mesaverde Formation, Cody Shale, Frontier Formation, and the Mowry Shale (fig. 7-2; Downey, 1986; Downey and Dinwiddie, 1988; Love and others, 1993; Merewether, 1996, figs. 4–6). The Meeteetse Formation in the eastern WRSB and eastern flanks of the Bighorn Mountains and adjacent areas, and the Lewis and Bearpaw Shales in the western PRSB are stratigraphically equivalent to the upper part of the Pierre Shale in the eastern PRSB. The Mesaverde Formation in the western PRSB and adjacent areas is stratigraphically equivalent to the middle Pierre Shale in the eastern PRSB. The Cody Shale in the western PRSB and adjacent areas is stratigraphically equivalent to the lower part of the Pierre Shale, Niobrara Formation, and the upper part of the Carlile Shale in the eastern PRSB. Stratigraphic names applied to strata equivalent to the upper part of the Cody Shale present in the southwestern PRSB and adjacent area differ between studies. Some studies identified the strata as the Steele Shale, a name assigned to similar or equivalent strata in the adjacent Laramie Mountains area (for example, Love and others, 1993), whereas other studies recognized the strata as the upper part of the Cody Shale or assigned the strata to an uppermost member of the Cody Shale identified as the Steele Member (for example, Nuccio, 1990; Merewether, 1996, fig. 4).

Most lithostratigraphic units composing the Upper Cretaceous confining unit are deeply buried, except where present at shallow depths or cropping out in small areas, primarily along the periphery of the PRSB and adjacent uplifted areas (plate 1). Thickness of the Upper Cretaceous confining unit in the PRSB increases to the south and southwest, ranging from less than 3,500 ft in northern Campbell County to 6,400 ft or more in southwestern Converse County (Downey, 1986, fig. 18; Fox and Higley, 1987a). Downey (1986) and Fox and Higley (1987a) identified the Mowry Shale as Lower Cretaceous in their studies, but Downey considered the Mowry Shale to be part of the Upper Cretaceous confining unit and included the formation in his thickness map, whereas Fox and Higley apparently did not include the Mowry Shale in their thickness map of Upper Cretaceous rocks from the base of the Fox Hills Sandstone to the top of the Lower Cretaceous rocks.

Lithostratigraphic units composing the Upper Cretaceous confining unit in the eastern PRSB and adjacent areas consist primarily of shale and other fine-grained mudrocks with very minor sandstone or other permeable lithologies, and thus are classified as or inferred to be individual confining units by previous studies, including the Pierre Shale, Niobrara Formation, Carlile Shale, Greenhorn Formation, Belle Fourche Shale, and the Mowry Shale (fig. 7-2; Warner, 1947; Babcock and Morris, 1954; Kohout, 1957; Whitcomb, 1960, 1965; Dana, 1962; Johnson, 1962; Whitcomb and Morris, 1964; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Wyoming Water Planning Program, 1972; Hodson and others, 1973; Feathers and others, 1981; Lowry and others, 1986). The Wyoming Water Framework Plan classified all of these lithostratigraphic units as major confining units (WWC Engineering and others, 2007, fig. 4-9). Some of these confining units have or are speculated to have locally water-saturated and permeable intervals likely capable of producing small quantities of water to wells, including interbedded thin and laterally discontinuous sandstone lenses/beds and locally fractured zones of shale or limestone (Whitcomb and Morris, 1964; Hodson and others, 1973; Feathers and others, 1981; Stock, 1981; Lowry and others, 1986). Limited use of these units as sources of water supply in the NERB study area was indicated by the few data not associated with petroleum exploration and development inventoried for this study, including only one well yield and one environmental water sample from one well completed in the Lewis confining unit, seven well yields and four environmental water samples from wells completed in the Pierre confining unit, and one spring discharge, eight well yields, and three environmental water samples from the Mowry Shale (plate 3; appendix E–2).

In contrast to the eastern PRSB and adjacent areas, sandstone beds of substantial thickness and areal extent are found interbedded with shale in several of the lithostratigraphic units composing the Upper Cretaceous confining unit in the western PRSB, eastern flank of the Bighorn Mountains, and Casper arch area. These sandstone beds are found in members of the Mesaverde Formation, Cody Shale, and Frontier Formation (Merewether, 1996, and references therein). Where water-saturated and permeable, the sandstone beds contain aquifers generally of local, rather than regional significance (Warner, 1947; Babcock and Morris, 1954; Kohout, 1957; Whitcomb, 1960, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a).

Sediments composing the Mesaverde Formation were deposited in marine and nonmarine environments (Gill and Burkholder, 1979; Merewether, 1996, and references therein). Thickness of the Mesaverde Formation in the PRSB increases from the north to south, and in Wyoming ranges from about 400 ft in Campbell County to as much as 1,200 ft in southern Converse County (Fox and Higley, 1987b; Merewether, 1996, fig. 22). Sandstone beds are found primarily in the uppermost member of the formation, known as the Teapot Sandstone Member, and the lowermost member, known as the Parkman Sandstone Member; the members are separated by an unnamed intervening unit known by various informal names, including the “unnamed member” or “unnamed marine shale member” (Wegemann, 1918; Gill and Cobban, 1966a, b, 1973; Merewether and others, 1977a, b, c, d; Gill and Burkholder, 1979; Merewether, 1996). Some studies elevate the Teapot and Parkman Sandstone Members to formation rank, and thus elevate the Mesaverde Formation to group rank (for example, Dogan, 1984).

Composed of marine and nonmarine, very fine- to medium-grained sandstone with locally occurring silty and sandy shale, coal, and shale pebbles, the Teapot Sandstone Member disconformably overlies either the unnamed marine shale member or the Parkman Sandstone Member, and is conformably overlain by the marine Lewis Shale (Gill and Cobban, 1966a, b; Gill and Burkholder, 1979; Dogan, 1984). Thickness of the Teapot Sandstone Member measured at outcrops in the western PRSB ranged from about 60 to 165 ft (Rich, 1962; Gill and Burkholder, 1979). In the subsurface, thickness of the Teapot Sandstone Member increases southward from less than 60 ft in northeastern Campbell County to more than 200 ft in a north-northwest-trending area in Converse, Campbell, Johnson, and Sheridan Counties (Fox and Higley, 1987c).

The marine shale member separating the two sandstone members is not present in all parts of the PRSB; the unit conformably overlies the Parkman Sandstone Member and is disconformably overlain by the Teapot Sandstone Member in parts of Converse, Natrona, and Johnson Counties, but it is replaced laterally by the Parkman Sandstone Member in southern and western Natrona County, northern Johnson County, and Sheridan County (Gill and Cobban, 1966a, b). The unnamed marine shale member is composed primarily of silty or sandy shale, clayey or sandy siltstone, and lesser amounts of very fine- to medium-grained sandstone (Gill and Burkholder, 1979). Although composed largely of fine-grained rocks, sandstone beds in the unnamed marine shale member can be as much as 155-ft thick (Gill and Burkholder, 1979).

The Parkman Sandstone Member is composed mainly of marine and nonmarine, thin-bedded, very fine- to fine-grained sandstone with partly carbonaceous and coaly, sandy shale (Merewether and others, 1977a, b, c, d; Dogan, 1984). In the western PRSB in Wyoming, the Parkman Sandstone Member conformably overlies and grades into the Cody Shale and is either conformably overlain by the unnamed marine shale member or is disconformably overlain by the Teapot Sandstone Member (Merewether and others, 1977a, b, c, d). Measurements at outcrops near the western PRSB indicate thickness of the Parkman Sandstone Member increases southward from about 356 ft in northwestern Sheridan County to about 553 ft in south-central Natrona County (Rich, 1962; Gill and Cobban, 1966a). In the subsurface, thickness of the Parkman Sandstone Member increases generally to the south from less than 75 ft in north-central Campbell County to about 700 ft in southwestern Converse County [Fox and Higley, 1987d (actual subsurface thickness likely smaller in some areas because mapped thickness in the report included Red Bird Silty Member of the Pierre Shale where present)].

On the basis of large sandstone content in the Teapot and Parkman Sandstone Members that compose much of the total formation thickness, the Mesaverde Formation is identified as an aquifer in previous studies (Warner, 1947; Babcock and Morris, 1954; Kohout, 1957; Whitcomb, 1960, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). Because sandstone is interbedded with substantial amounts of shale throughout the formation, Western Water Consultants, Inc. (1983, fig. 2) described the Mesaverde Formation in the southwestern PRSB near the town of Kaycee as a "secondary aquifer with leaky confining layers." The Mesaverde Formation in the NERB study area was classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). In this study, the Mesaverde Formation also is considered an aquifer (fig. 7-2); however, the unit is still considered part of the regionally extensive Upper Cretaceous confining unit because net thickness of water-saturated and permeable sandstone composing the aquifer (likely hundreds of feet) is still very small in comparison with the thousands of feet of fine-grained low-permeability strata (primarily shale) in the various overlying and underlying lithostratigraphic units composing the confining unit (Downey, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996).

Development of the Mesaverde aquifer as a water supply in the NERB study area is limited to areas in or near outcrops along the PRSB margin and adjacent Casper arch area where water-saturated and sufficiently permeable sandstone beds can be penetrated at economical drilling depths, and where groundwater is likely to be fresher and less mineralized (Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981). Wells completed in the Mesaverde aquifer in these areas are used primarily to provide water for stock supply. Crist and Lowry (1972) suggested that both the Teapot and Parkman Sandstone Members should be fully penetrated to provide maximum yield from wells completed in the Mesaverde aquifer.

Hydrogeologic data describing physical characteristics of the Mesaverde aquifer in the NERB study area, including well-yield measurements and other hydraulic properties, are summarized on plate 3. Hodson and others (1973) speculated that yields of as much as 50 gal/min likely were possible from sandstone beds in the Mesaverde aquifer, and that yields of as much as 200 gal/min were possible in areas where fracturing has increased permeability. Well yields from 26 wells completed in the Mesaverde aquifer inventoried as part of this study indicated generally smaller yields than predicted by Hodson and others (1973). Yields from these 26 wells ranged from than 0.5 to 130 gal/min, with a median of 11 gal/min (plate 3); however, most of these wells likely did not fully penetrate the numerous water-saturated and permeable sandstone beds present throughout the formation at most locations. Except near outcrop areas, groundwater in the Mesaverde aquifer generally is under confined conditions at most locations (Feathers and others, 1981). Kohout (1957) noted that recharge to the Mesaverde aquifer in the southwestern PRSB near Kaycee likely was by infiltration of precipitation on outcrops and streamflow losses (seepage) from the Middle and South Forks of the Powder River.

Composed primarily of thousands of feet of dark gray marine shale conformably underlying and interfingering with the Mesaverde Formation and conformably overlying the Frontier Formation, the Cody Shale is inferred to be or is defined as a confining unit or major regional confining unit by previous investigators, and that definition is retained herein (fig. 7-2; Warner, 1947; Babcock and Morris, 1954; Kohout, 1957; Whitcomb, 1960, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983; Downey, 1986; Busby and others, 1995). The Cody Shale was classified as a major confining unit in the Wyoming Water Framework Plan (WWC Engineering and others, 2007). Substantial widespread shoreface and nearshore marine sandstone beds are found in the upper part of the Cody Shale. Encased by and interbedded with the marine shale that composes most of the Cody Shale, these beds consist primarily of fine-grained sandstone with lesser siltstone and shale that have been assigned to formally recognized members of the Cody Shale, including two lithostratigraphic units identified as the Sussex and Shannon Sandstone Members (Wegemann, 1911; Wilson, 1951; Berg, 1975; Crews and others, 1976; Tillman and Martinsen, 1984; Merewether, 1996, and references therein). Sandstone bed geometry of the Sussex and Shannon Sandstone Members in the PRSB is dominated by northwest-southeast-trending linear sandstone units/ridges (Hansley and Whitney, 1990; Higley, 1992; Anna, 2010). Individual sandstone beds in the Sussex Sandstone Member are tens of feet thick, 2 to 3 miles wide, and tens of miles in length; individual sandstone beds in the Shannon Sandstone Member are as much as 50-ft thick, thousands of feet in width, and tens of miles in length (Hansley and Whitney, 1990; Higley, 1992; Anna, 2010). Building upon previous studies, Craddock and others (2012, and references therein) reported that net sandstone thickness of the combined Sussex and Shannon Sandstone Members in the PRSB varied substantially, and averaged about 95±25 ft.

Where water-saturated and permeable, sandstone beds of the Sussex and Shannon Sandstone Members of the Cody Shale are speculated to be or are defined as low-yielding aquifers, with yields generally less than 20 gal/min

(Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Wyoming Water Planning Program, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). Most water produced from the Cody Shale not associated with petroleum production likely is from these two members (Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981). Maximum yield for wells completed in the Cody confining unit inventoried as part of this study was 19 gal/min (range of 0.25–19 gal/min with median of 5 gal/min), very close to the maximum yield (20 gal/min) estimated or reported for the Sussex and Shannon Sandstone Members in previous studies (plate 3; unknown if all wells inventoried as part of this study were completed exclusively in these members). Both members were identified as individual minor aquifers ("Sussex and Shannon aquifers") within the thick Cody Shale/confining unit by Feathers and others (1981). The Sussex and Shannon Sandstone Members are important petroleum reservoirs in the west and central parts of the PRSB, and most wells penetrating these units were installed for petroleum exploration and development, typically at great depths (thousands of feet) necessary for petroleum generation and accumulation (Crews and others, 1976; Dolton and others, 1990; Hansley and Whitney, 1990; Higley, 1992; Anna, 2010). Most available hydrogeologic data describing the physical and chemical characteristics of the Cody confining unit, including the Sussex and Shannon Sandstone Members, are from wells associated with this exploration and development; these wells typically are installed at depths that are not economically feasible for other uses. In addition, groundwater from these aquifers typically has very poor water-quality characteristics, as indicated by produced-water samples inventoried for this study and described in the "Cody confining unit" section; consequently, the Cody confining unit, including the Sussex and Shannon Sandstone Members, are rarely used sources of water in the NERB study area because of deep burial, poor water quality throughout their geographic extent, and availability of water from shallower aquifers. Development of the Cody confining unit, including the Sussex and Shannon Sandstone Members, as sources of water supply in the NERB study area is limited to areas in or near outcrops along the PRSB perimeter where sufficiently water-saturated and permeable sandstone beds can be penetrated at economical drilling depths and where groundwater is likely to be fresher and less mineralized. Even in these areas, groundwater quality can be very poor and unsuitable for most uses without treatment (for example, Babcock and Morris, 1954; Wyoming State Engineer's Office, 1963; Western Water Consultants, Inc., 1982a; this study). Hydrogeologic data describing the physical characteristics of the Cody confining unit in the NERB study area, including well-yield measurements and other hydraulic properties, are summarized on plate 3. In addition, hydrogeologic data collected during petroleum exploration and development from hydrocarbon-producing strata assigned by petroleum producers to the Steele Shale/Member (identified herein as the Steele confining unit, and composed of strata that are considered an upper member/part of the Cody Shale in some studies; Merewether, 1996), are summarized separately from the Cody Shale on plate 3.

Marine and nonmarine siliciclastic sediments composing the Frontier Formation in what is now the western and southwestern PRSB were deposited in numerous depositional environments (Hares, 1916; Towse, 1952; Merewether and others, 1979, and references therein; Merewether, 1996, and references therein). Thickness of the Frontier Formation in the PRSB ranges from about 400 to 1,000 ft, and is greatest in the eastern half of Natrona County and in the southern half of Converse County (Merewether, 1996). Two or three different members of the Frontier Formation are recognized, including, from stratigraphically youngest to oldest, the Wall Creek Sandstone (also known as the Wall Creek Member; Merewether, 1996), Emigrant Gap Member (formerly known as the "unnamed member"; Merewether and others, 1979), and the Belle Fourche Shale (Wegemann, 1911; Hares, 1916; Hose, 1955; Mapel, 1959; Merewether and others, 1979; Merewether, 1996) (also known as the Belle Fourche Member; Merewether, 1996). All three members are not present at all locations in the PRSB and adjacent areas. For example, the Frontier Formation is composed only of the Wall Creek Sandstone and Belle Fourche Shale in southern Johnson County (Hose, 1955; Mapel, 1959; Merewether and others, 1979; Merewether, 1996). Some of the members grade laterally into other lithostratigraphic units, as Merewether (1996) noted in northern Johnson County that the Wall Creek Sandstone (identified by investigator as the Wall Creek Member) grades laterally into the lower part of the Cody Shale, and in this area the Belle Fourche Shale (identified by investigator as the Belle Fourche Member) is elevated to formation rank and assigned to the Belle Fourche Formation, and the name Frontier Formation is no longer retained. The Wall Creek Sandstone consists of very fine- to fine-grained sandstone, silty sandstone, siltstone, sandy siltstone, silty shale, and shale; the sandstone beds generally grade into underlying siltstone, and are abruptly overlain by shale or siltstone (Merewether and others, 1979; Merewether, 1996). Sandstone content and thickness of the Wall Creek Sandstone is greatest in the southwestern PRSB; thickness in this area ranges from

10 to 280 ft (Merewether, 1996). In the southwestern PRSB, the Wall Creek Sandstone disconformably overlies either the Emigrant Gap Member or the Belle Fourche Member and is conformably overlain by the Cody Shale (Merewether and others, 1979; Merewether, 1996). Composition of the Emigrant Gap and Belle Fourche Shale is similar to the Wall Creek Sandstone, consisting primarily of interstratified very fine- to medium-grained sandstone, siltstone, and mudstone; the sandstone is locally conglomeratic, calcareous, and concretionary (Merewether and others, 1979; Merewether, 1996). Anna (2010) estimated that fine-grained rocks composed about one-half of total formation thickness. Thickness of the Emigrant Gap Member in the southwestern part of the PRSB is as much as 140 ft in east-central Natrona County. Thickness of the Belle Fourche Shale in southern Johnson County, Natrona County, and western Converse County ranges from about 591 to 787 ft (Merewether, 1996, fig. 9C). In the subsurface, thickness of the Belle Fourche Shale is about 570 ft in southwestern Campbell County and 600 ft in east-central Natrona County (Merewether, 1996, fig. 9C).

Because of substantial sandstone content, the Frontier Formation is speculated to be or is defined as an aquifer by previous investigators, and that definition is retained herein (fig. 7-2; Warner, 1947; Babcock and Morris, 1954; Kohout, 1957; Whitcomb, 1960, 1965; Lowry and Cummings, 1966; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). Water-saturated and permeable sandstone beds are interbedded with substantial amounts of fine-grained rocks throughout the formation, so Western Water Consultants, Inc. (1983, fig. 2) described the Frontier Formation in the southwestern PRSB near the town of Kaycee as a series of "alternating leaky confining layers and secondary aquifers." The Frontier Formation in the NERB study area was classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007). Although classified as an aquifer herein, the Frontier Formation is still considered part of the regionally extensive Upper Cretaceous confining unit because net thickness of water-saturated and permeable sandstone composing the aquifer (likely hundreds of feet) is still very small in comparison with the thousands of feet of fine-grained low-permeability strata (primarily shale) in the various overlying lithostratigraphic units and hundreds of feet in underlying units composing the confining unit (Downey, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996).

Development of the Frontier aquifer as a water supply in the NERB study area is limited to areas in or near outcrops along the PRSB margin and adjacent Casper arch area in Natrona County where sufficiently water-saturated and permeable sandstone beds can be penetrated at economical drilling depths and where groundwater is likely to be fresher and less mineralized (Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1983, fig. 2; Banner Associates, Inc., 2002). Many groundwater wells have been completed in the Frontier aquifer in these areas, many of which have artesian pressure sufficient to cause wells completed in the aquifer to flow (plate 3; Crist and Lowry, 1972; Banner Associates, Inc., 2002). Much of the water withdrawn from the Frontier aquifer is used to provide water for stock supply. Several investigators have noted the potential for development of secondary porosity and permeability from fractures in the sandstones composing the Frontier aquifer (Western Water Consultants, Inc., 1983, fig. 2; Banner Associates, Inc., 2002). Except near outcrop areas, groundwater in the Frontier aquifer generally is under confined conditions at most locations (Feathers and others, 1981). Warner (1947) speculated that recharge to the Wall Creek Sandstone of the Frontier Formation in the southwestern PRSB near Kaycee was by infiltration of precipitation on outcrops and streamflow losses (seepage) from the Middle Fork of the Powder River. Hydrogeologic data describing the physical characteristics of the Frontier aquifer in the NERB study area, including well-yield measurements and other hydraulic properties, are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the individual hydrogeologic units composing the Upper Cretaceous confining unit in the NERB study area are described using environmental and produced-water samples in this section of the report. Chemical characteristics are described almost entirely using produced-water samples because most hydrogeologic units composing the Upper Cretaceous confining unit are rarely developed as sources of water supply because of deep burial and poor water quality except near outcrop areas. Groundwater quality of the hydrogeologic units 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 groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

Lewis confining unit

The chemical composition of groundwater from the Lewis confining unit in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram C). The TDS concentration from the well (739 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L). No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) was measured at a concentration greater than the aesthetic standard for domestic use (SMCL limit of 500 mg/L). One characteristic (SAR) and one constituent (sulfate) had values greater than the applicable State of Wyoming standard for agricultural use (WDEQ Class II standards of 8 and 200 mg/L, respectively). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Lewis confining unit in the NERB study area also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram C). TDS concentrations indicated that produced waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L). TDS concentrations ranged from 1,027 to 2,519 mg/L, with a median of 1,252 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples at concentrations greater than aesthetic standards for domestic use include: TDS (all 3 samples exceeded SMCL limit of 500 mg/L), pH (1 of 2 samples above upper SMCL limit of 8.5), and chloride (1 of 3 samples exceeded SMCL limit of 250 mg/L).

Several characteristics and constituents were measured in produced-water samples from the Lewis confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (2 of 3 samples exceeded WDEQ Class II standard of 8), chloride (2 of 3 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (2 of 3 samples exceeded WDEQ Class II standard of 200 mg/L), and TDS (1 of 3 samples exceeded WDEQ Class II standard of 2,000 mg/L). One characteristic (pH) was measured at a concentration greater than livestock-use standards (1 of 2 samples above upper WDEQ Class III limit of 8.5).

Pierre confining unit

The chemical composition of groundwater from the Pierre confining unit in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram D). TDS concentrations indicate that the waters were fresh (3 of 4 samples, concentrations less than or equal to 999 mg/L) to slightly saline (1 of 4 samples, concentrations between 1,000 to 2,999 mg/L) (appendix E–2; appendix I–2, diagram D). TDS concentrations ranged from 276 to 1,510 mg/L, with a median of 591 mg/L.

Several characteristics and constituents were measured in environmental water samples from the Pierre confining unit in the NERB study area at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic and one constituent were measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use: TDS (3 of 4 samples exceeded the SMCL of 500 mg/L) and sulfate (1 of 4 samples exceeded the SMCL of 250 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Pierre confining unit in the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. One constituent and one characteristic were measured at concentrations greater than agricultural-use standards: sulfate (2 of 4 samples exceeded the WDEQ Class II standard of 200 mg/L) and SAR (1 of 4 samples exceeded WDEQ Class II standard of 8). No characteristics or constituents had concentrations that exceeded applicable State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Pierre confining unit in the NERB study area also was characterized and the quality evaluated on the basis of 39 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram D). TDS concentrations were variable and indicated that most produced waters were very saline (20 of 39 samples, concentration ranging from 10,000 to 34,999 mg/L) to moderately saline (18 of 39 samples, concentrations ranging from 3,000 to 9,999 mg/L), and the remaining sample was briny (1 of 39 concentrations greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram D). TDS concentrations ranged from 3,399 to 37,370 mg/L, with a median of 10,480 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples at concentrations greater than aesthetic standards for domestic use include: TDS (all 39 samples exceeded SMCL limit of 500 mg/L), chloride (all 39 samples exceeded SMCL limit of 250 mg/L), iron (2 of 3 quantified samples exceeded the SMCL of 300 µg/L), pH (5 of 28 samples above upper SMCL limit of 8.5), and sulfate (5 of 35 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water water samples from the Pierre confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: SAR (all 39 samples exceeded WDEQ Class II standard of 8), TDS (all 39 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (all 39 samples exceeded WDEQ Class II standard of 100 mg/L), and sulfate (8 of 35 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (37 of 39 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (35 of 39 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (5 of 28 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 21 of 39 produced-water samples.

Mesaverde aquifer

The chemical composition of groundwater from the Mesaverde aquifer in the PRSB part of the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as seven wells. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram E). TDS concentrations indicated that most waters were slightly saline (4 of 7 samples, concentrations between 1,000 to 2,999 mg/L) to fresh (2 of 7 samples, concentrations less than or equal to 999 mg/L), and the remaining water was moderately saline (1 of 7 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–2; appendix I–2, diagram E). TDS concentrations ranged from 370 to 4,430 mg/L, with a median of 1,490 mg/L.

Several characteristics and constituents were measured in environmental water samples from the Mesaverde aquifer at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (nitrate plus nitrite) was measured at a concentration greater than a health-based standard (1 of 2 samples exceeded the USEPA MCL of 10 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (6 of 7 samples exceeded the SMCL of 500 mg/L), sulfate (5 of 7 samples exceeded the SMCL of 250 mg/L), pH (1 of 7 samples above upper SMCL limit of 8.5), and fluoride (1 of 7 samples exceeded the SMCL of 2 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Mesaverde aquifer in the PRSB part of the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: SAR (5 of 7 samples exceeded WDEQ Class II standard of 8), sulfate (5 of 7 samples exceeded the WDEQ Class II standard of 200 mg/L), and TDS (3 of 7 samples exceeded WDEQ Class II standard of 2,000 mg/L). One constituent and one characteristic were measured at concentrations greater than livestock-use standards: nitrate plus nitrite (1 of 2 samples exceeded WDEQ Class III standard of 100 mg/L) and pH (1 of 7 samples above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater from the Mesaverde aquifer in the PRSB part of the NERB study area also was characterized and the quality evaluated on the basis of 466 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram E). TDS concentrations from produced-water samples were variable and indicated that waters were very saline (349 of 463 samples, concentrations ranging from 10,000 to 34,999 mg/L), moderately saline (75 of 463 samples, concentrations ranging from 3,000 to 9,999 mg/L), slightly saline (32 of 463 samples, concentrations ranging from 1,000 to 2,999 mg/L), fresh (2 of 463 samples, concentrations less than or equal to 999 mg/L), and briny (5 of 463 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram E). TDS concentrations ranged from 399 to 48,670 mg/L, with a median of 14,170 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included constituents that could be compared to health-based standards, including fluoride (all 3 samples exceeded the USEPA MCL of 4 mg/L) and boron (6 of 7 samples exceeded the USEPA HAL of 6,000 μg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: fluoride (all 3 samples exceeded the SMCL of 2 mg/L), TDS (462 of 463 samples exceeded SMCL limit of 500 mg/L), chloride (444 of 466 samples exceeded SMCL limit of 250 mg/L), iron (152 of 155 quantified samples exceeded the SMCL of 300 μg/L), sulfate (67 of 341 samples exceeded SMCL of 250 mg/L), and pH (8 of 391 samples below the lower SMCL limit of 6.5 and 25 of 391 samples above upper SMCL limit of 8.5).

Many characteristics and constituents were measured in produced-water samples from the Mesaverde aquifer in the PRSB part of the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: boron (all 7 samples exceeded WDEQ Class II standard of 750 μg/L), SAR (464 of 466 samples exceeded WDEQ Class II standard of 8), chloride (451 of 466 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (439 of 463 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (90 of 155 quantified samples exceeded WDEQ Class II standard of 5,000 μg/L), sulfate (81 of 341 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (1 of 391 samples exceeded upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (402 of 463 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (400 of 466 samples exceeded WDEQ Class III standard of 2,000 mg/L), boron (6 of 7 samples exceeded WDEQ Class III standard of 5,000 μg/L), pH (8 of 391 samples below lower WDEQ Class III limit of 6.5 and 25 of 391 samples above upper WDEQ Class III limit of 8.5), and sulfate (1 of 341 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 354 of 463 produced-water samples.

Cody confining unit

The chemical composition of groundwater from the Cody confining unit in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram F). One TDS concentration (780 mg/L) indicated fresh water (TDS concentrations less than 1,000 mg/L), whereas the other TDS concentration (12,600 mg/L) indicated very saline water (TDS concentrations greater than or equal to 10,000 and less than or equal to 34,999 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Cody confining unit at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic and one constituent were measured in both samples at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use: TDS (exceeded the SMCL of 500 mg/L) and sulfate (exceeded the SMCL of 250 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Cody confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (both samples exceeded the WDEQ Class II standard of 200 mg/L), boron (the one sample analyzed exceeded WDEQ Class II standard of 750 μg/L), SAR (one sample exceeded WDEQ Class II standard of 8), TDS (one sample exceeded WDEQ Class II standard of 2,000 mg/L), and chloride (one sample exceeded WDEQ Class II standard of 100 mg/L). One characteristic and one constituent were measured in one sample at concentrations greater than livestock-use standards, including TDS (exceeded WDEQ Class III standard of 5,000 mg/L) and sulfate (exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in one of the environmental water samples.

The chemical composition of groundwater from the Cody confining unit in the NERB study area also was characterized and the quality evaluated on the basis of 415 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram F). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (209 of 415 samples, concentrations ranging from 10,000 to 34,999 mg/L) to moderately saline (119 of 415 samples, concentrations ranging from 3,000 to 9,999 mg/L), and remaining waters were briny (66 of 415 samples, concentrations greater than or equal to 35,000 mg/L), slightly saline (20 of 415 samples, concentrations ranging from 1,000 to 2,999 mg/L), and fresh (1 of 415 samples, concentrations less than or equal to 999 mg/L) (appendix G–2; appendix K–2, diagram F). TDS concentrations ranged from 97.2 to 76,100 mg/L, with a median of 13,400 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included one constituent (boron) that could be compared to health-based standards (1 of 2 samples exceeded the USEPA HAL of 6,000 μg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: iron (all 103 quantified samples exceeded the SMCL of 300 μg/L), TDS (414 of 415 samples exceeded SMCL limit of 500 mg/L), chloride (389 of 415 samples exceeded SMCL limit of 250 mg/L), sulfate (44 of 290 samples exceeded SMCL of 250 mg/L), and pH (21 of 380 samples below lower SMCL limit of 6.5 and 26 of 380 samples above upper SMCL limit of 8.5).

Many characteristics and constituents were measured in produced-water water samples from the Cody confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: boron (both samples exceeded WDEQ Class II standard of 750 μg/L), SAR (412 of 414 samples exceeded WDEQ Class II standard of 8), TDS (401 of 415 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (398 of 415 samples exceeded WDEQ Class II standard of 100 mg/L), iron (89 of 103 samples exceeded WDEQ Class II standard of 5,000 μg/L), sulfate (47 of 290 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (5 of 380 samples exceeded upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include TDS (363 of 415 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (338 of 415 samples exceeded WDEQ Class III standard of 2,000 mg/L), boron (1 of 2 samples exceeded WDEQ Class III standard of 5,000 μg/L), pH (21 of 380 samples below lower WDEQ Class III limit of 6.5 and 26 of 380 samples above upper WDEQ Class III limit of 8.5), and sulfate (4 of 290 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 274 of 415 produced-water samples.

Steele confining unit

The chemical composition of groundwater from the Steele confining unit in the NERB study area was characterized and the quality evaluated on the basis of 33 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram G). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (22 of 33 samples, concentrations ranging from 3,000 to 9,999 mg/L), and the remaining samples were very saline (9 of 33 samples, concentration ranging from 10,000 to 34,999 mg/L) to slightly saline (2 of 33 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix G–2; appendix K–2, diagram G). TDS concentrations ranged from 1,989 to 10,960 mg/L, with a median of 8,087 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 33 samples exceeded SMCL limit of 500 mg/L), chloride (31 of 33 samples exceeded SMCL limit of 250 mg/L), pH (2 of 33 samples above upper SMCL limit of 8.5), and sulfate (1 of 26 samples exceeded SMCL of 250 mg/L). Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 33 samples exceeded WDEQ Class II standard of 8), chloride (all 33 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (32 of 33 samples exceeded WDEQ Class II standard of 2,000 mg/L), and sulfate (1 of 26 samples exceeded WDEQ Class II standard of 200 mg/L). Two characteristics and one constituent were measured at concentrations greater than livestock-use standards: TDS (28 of 33 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (25 of 33 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (2 of 33 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 9 of 33 produced-water samples.

Niobrara confining unit

The chemical composition of groundwater from the Niobrara confining unit in the NERB study area was characterized and the quality evaluated on the basis of 32 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram H). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (19 of 32 samples, concentration ranging from 10,000 to 34,999 mg/L) to briny (7 of 32 samples, concentrations greater than or equal to 35,000 mg/L), and the remaining samples were moderately saline (5 of 32 samples, concentration ranging from 3,000 to 9,999 mg/L) to slightly saline (1 of 32 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix G–2; appendix K–2, diagram H). TDS concentrations ranged from 1,984 to 47,800 mg/L, with a median of 25,220 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 32 samples exceeded SMCL limit of 500 mg/L), chloride (31 of 32 samples exceeded SMCL limit of 250 mg/L), iron (all 4 quantified samples exceeded the SMCL of 300 µg/L), pH (1 of 8 samples below the lower SMCL limit of 6.5), and sulfate (2 of 29 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water water samples from the Niobrara confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 32 samples exceeded WDEQ Class II standard of 8), chloride (all 32 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (31 of 32 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (2 of 4 quantified samples exceeded WDEQ Class II standard of 5,000 µg/L), and sulfate (2 of 29 samples exceeded WDEQ Class II standard of 200 mg/L). Two characteristics and one constituent were measured at concentrations greater than livestock-use standards, including TDS (30 of 32 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (28 of 32 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (1 of 8 samples below lower WDEQ Class III limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 26 of 32 produced-water samples.

Carlile confining unit

The chemical composition of groundwater from the Carlile confining unit in the NERB study area was characterized and the quality evaluated on the basis of as many as 70 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram I). TDS concentrations from produced-water samples were variable and indicated that most waters were briny (52 of 70 samples, concentrations greater than or equal to 35,000 mg/L) to very saline (13 of 70 samples, concentrations ranging from 10,000 to 34,999 mg/L), and remaining waters were moderately saline (3 of 70 samples, concentrations ranging from 3,000 to 9,999 mg/L), fresh (1 of 70 samples, concentrations less than or equal to 999 mg/L), and slightly saline (1 of 70 samples, concentration ranging from 1,000 to 2,999 mg/L) appendix G–2; appendix K–2, diagram I). TDS concentrations ranged from 86.2 to 84,100 mg/L, with a median of 40,350 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One produced-water sample included two constituents that could be compared to health-based standards: boron (exceeded the USEPA HAL of 6,000 µg/L) and fluoride (exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: fluoride (the one sample analyzed for this constituent exceeded the SMCL of 2 mg/L), TDS (69 of 70 samples exceeded SMCL limit of 500 mg/L), chloride (67 of 70 samples exceeded SMCL limit of 250 mg/L), iron (8 of 9 samples exceeded the SMCL of 300 µg/L), pH (3 of 16 samples above upper SMCL limit of 8.5), and sulfate (4 of 63 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water samples from the Carlile confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 70 samples exceeded WDEQ Class II standard of 8), boron (the one sample analyzed for this constituent exceeded WDEQ Class II standard of 750 µg/L), TDS (68 of 70 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (69 of 70 samples exceeded WDEQ Class II standard of 100 mg/L), iron (6 of 9 samples exceeded WDEQ Class II standard of 5,000 µg/L), pH (1 of 16 samples exceeded upper WDEQ Class II standard of 9), and sulfate (4 of 63 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards include: boron (the one sample analyzed for this constituent exceeded WDEQ Class III standard of 5,000 µg/L), TDS (66 of 70 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (66 of 70 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (3 of 16 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 65 of 70 produced-water samples.

Frontier aquifer

The chemical composition of groundwater from the Frontier aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 14 wells. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram G). TDS concentrations indicated that waters were slightly saline (8 of 12 samples, concentration ranging from 1,000 to 2,999 mg/L) and fresh (4 of 12 samples, concentrations less than or equal to 999 mg/L) (appendix E–2; appendix I–2, diagram G). TDS concentrations ranged from 348 to 2,270 mg/L, with a median of 1,120 mg/L.

Several characteristics and constituents were measured in environmental water samples from the Frontier aquifer at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured at a concentration greater than the health-based standard (1 of 11 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (10 of 12 samples exceeded the SMCL of 500 mg/L), pH (7 of 11 samples above upper SMCL limit of 8.5), sulfate (8 of 14 samples exceeded the SMCL of 250 mg/L), and fluoride (2 of 11 samples exceeded the SMCL of 2 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Frontier aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (9 of 14 samples exceeded the WDEQ Class II standard of 200 mg/L), SAR (5 of 13 samples exceeded WDEQ Class II standard of 8), boron (2 of 7 samples exceeded WDEQ Class II standard of 750 µg/L), TDS (3 of 12 samples exceeded WDEQ Class II standard of 2,000 mg/L), and chloride (2 of 14 samples exceeded WDEQ Class II standard of 100 mg/L). One characteristic (pH) was measured at values outside the range for livestock use (7 of 11 samples above upper WDEQ Class III limit of 8.5).

The chemical composition of the Frontier aquifer in the PRSB part of the NERB study area also was characterized and the quality evaluated on the basis of 321 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram J). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (167 of 320 samples, concentrations ranging from 3,000 to 9,999 mg/L) to very saline (86 of 320 samples, concentrations ranging from 10,000 to 34,999 mg/L), and remaining waters were slightly saline (43 of 320 samples, concentrations ranging from 1,000 to 2,999 mg/L), briny (18 of 320 samples, concentrations greater than or equal to 35,000 mg/L), and fresh (6 of 320 samples, concentrations less than or equal to 999 mg/L) (appendix G–2; appendix K–2, diagram J). TDS concentrations ranged from 227 to 156,600 mg/L, with a median of 7,019 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included two constituents that could be compared to health-based standards: fluoride (the one sample analyzed for this constituent exceeded the USEPA MCL of 4 mg/L) and boron (2 of 3 samples exceeded the USEPA HAL of 6,000 µg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: fluoride (the one sample analyzed for this constituent exceeded the SMCL of 2 mg/L), TDS (315 of 320 samples exceeded SMCL limit of 500 mg/L), chloride (285 of 321 samples exceeded SMCL limit of 250 mg/L), iron (11 of 12 samples exceeded the SMCL of 300 µg/L), sulfate (119 of 284 samples exceeded SMCL of 250 mg/L), and pH (7 of 265 samples below lower SMCL limit of 6.5 and 51 of 265 samples above upper SMCL limit of 8.5).

Many characteristics and constituents were measured in produced-water samples from the Frontier aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: boron (all 3 samples exceeded WDEQ Class II standard of 750 µg/L), SAR (307 of 316 samples exceeded WDEQ Class II standard of 8), chloride (306 of 321 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (298 of 320 samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (125 of 284 samples exceeded WDEQ Class II standard of 200 mg/L), iron (7 of 12 quantified samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (1 of 265 samples below lower WDEQ Class II limit of 4.5 and 10 of 265 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: boron (2 of 3 samples exceeded WDEQ Class III standard of 5,000 µg/L), TDS (205 of 320 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (162 of 321 samples exceeded WDEQ Class III standard of 2,000 mg/L), pH (7 of 265 samples below lower WDEQ Class III limit of 6.5 and 51 of 265 samples above upper WDEQ Class III limit of 8.5), and sulfate (7 of 284 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 104 of 320 produced-water samples.

Greenhorn confining unit

The chemical composition of groundwater from the Greenhorn confining unit in the NERB study area was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram K). The TDS concentrations (18,420 and 20,670 mg/L) indicated that the waters were very saline (TDS concentrations greater than or equal to 10,000 and less than or equal to 34,999 mg/L).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One characteristic (TDS) and one constituent (chloride) were measured in both samples at concentrations greater than aesthetic standards for domestic use (SMCLs of 500 mg/L and 250 mg/L, respectively). Two characteristics (SAR and TDS) and one constituent (chloride) were measured in both samples at concentrations greater than agricultural-use standards (WDEQ Class II standards of 8, 2,000 mg/L, and 100 mg/L, respectively). One characteristic (TDS) and one constituent (chloride) were measured in both samples at concentrations greater than livestock-use standards (WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

Mowry confining unit

The chemical composition of groundwater from the Mowry confining unit in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram H). The TDS concentration from one well (765 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L).

Several characteristics and constituents were measured in one environmental water sample from the Mowry confining unit at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) and one constituent (sulfate) were measured at concentrations greater than USEPA aesthetic standards for domestic use (SMCLs of 500 mg/L and 250 mg/L, respectively). One constituent (sulfate) was measured at a concentration greater than State of Wyoming agricultural water-quality standards (WDEQ Class II standard of 200 mg/L). No characteristics or constituents were measured at concentrations greater than State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Mowry confining unit in the PRSB part of the NERB study area 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 G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram L). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (5 of 9 samples, concentration ranging from 10,000 to 34,999 mg/L) to briny (3 of 9 samples, concentrations greater than or equal to 35,000 mg/L), and remaining waters were slightly saline (1 of 9 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix G–2; appendix K–2, diagram L). TDS concentrations ranged from 1,608 to 38,600 mg/L, with a median of 27,500 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Two produced-water samples included constituents that could be compared to health-based standards, including boron (both samples exceeded the USEPA HAL of 6,000 µg/L), selenium (the one sample exceeded the USEPA MCL of 50 µg/L), and fluoride (1 of 2 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 9 samples exceeded SMCL limit of 500 mg/L), chloride (8 of 9 samples exceeded SMCL limit of 250 mg/L), fluoride (1 of 2 samples exceeded the SMCL of 2 mg/L), and sulfate (2 of 9 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water water samples from the Mowry confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 9 samples exceeded WDEQ Class II standard of 8), boron (both samples exceeded WDEQ Class II standard of 750 µg/L), selenium (the one sample exceeded WDEQ Class II standard of 20 µg/L), TDS (8 of 9 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (8 of 9 samples exceeded WDEQ Class II standard of 100 mg/L), and sulfate (2 of 9 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards include: boron (both samples exceeded WDEQ Class III standard of 5,000 µg/L), selenium (the one sample exceeded WDEQ Class III standard of 50 µg/L), TDS (8 of 9 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (7 of 9 samples exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate (2 of 9 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 8 of 9 produced-water samples.

7.3.2.1 Lance aquifer (Wind River structural basin)

The physical and chemical characteristics of the Lance aquifer in the part of the WRSB within the NERB study area are described in this section of the report.

Physical characteristics

Water-saturated and permeable parts of the Late Cretaceous-age Lance Formation compose the Lance aquifer in the WRSB (Bartos and others, 2012, plate II). The Lance aquifer in the WRSB is grouped in some studies with the overlying Fort Union aquifer into a broader hydrogeologic unit identified as the Fort Union-Lance aquifer (Bartos and others, 2012, plate II). The Lance Formation in the WRSB 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 part of the WRSB to more than 6,000 ft along the basin trough south of the Bighorn Mountains (Johnson and others, 2007, fig. 15). The aquifer is overlain by the Fort Union aquifer and underlain by the Meeteetse-Lewis confining unit (Bartos and others, 2012, plate II). Confined conditions predominate, but unconfined conditions are likely in outcrop areas. With the exception of oil and gas wells, very few wells have been installed in the Lance aquifer in the WRSB. Richter (1981, table IV-1, p. 48) speculated the aquifer had “large development potential” in the WRSB, but poor water quality reported by Bartos and others (2012) and this study (determined primarily from produced water samples from deeply buried parts of the aquifer) would preclude most uses without treatment.

Chemical characteristics

The chemical characteristics of groundwater from the Lance aquifer in the WRSB are described using produced-water samples in this section of the report. Groundwater quality of the Lance aquifer is described in terms of a water’s suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix H).

The chemical composition of groundwater from the Lance aquifer in the WRSB was characterized and the quality evaluated on the basis of 33 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram C). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (23 of 33 samples, concentrations ranging from 3,000 to 9,999 mg/L) to very saline (7 of 33 samples, concentrations ranging from 10,000 to 34,999 mg/L), and remaining waters were slightly saline (3 of 33 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix H; appendix L, diagram C). TDS concentrations ranged from 2,236 to 21,520 mg/L, with a median of 5,750 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 33 samples exceeded SMCL limit of 500 mg/L), chloride (31 of 33 samples exceeded SMCL limit of 250 mg/L), iron (8 of 14 samples exceeded the SMCL of 300 µg/L), sulfate (11 of 30 samples exceeded SMCL of 250 mg/L), and pH (8 of 33 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Lance aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 33 samples exceeded WDEQ Class II standard of 8), TDS (all 33 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (32 of 33 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (13 of 30 samples exceeded WDEQ Class II standard of 200 mg/L), iron (3 of 14 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (1 of 33 samples exceeded upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (22 of 33 samples exceeded WDEQ Class III standard of 5,000 mg/L), pH (8 of 33 samples above upper WDEQ Class III limit of 8.5), chloride (9 of 33 samples exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate (1 of 30 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 7 of 33 produced-water samples.

7.3.2.2 Meeteetse confining unit (Wind River structural basin)

The physical and chemical characteristics of the Meeteetse confining unit in the part of the WRSB within the NERB study area are described in this section.

Physical characteristics

The Late-Cretaceous age Meeteetse Formation in the WRSB consists of thin-bedded to massive sandstone, shale, claystone, siltstone, mudstone, and occasional thin coal (Johnson and others, 2007). The Meeteetse Formation and Lewis Shale are overlain by the Lance Formation and underlain by the Mesaverde Formation (Bartos and others, 2012, plate II). Reported thickness of the Meeteetse Formation ranges from 500 ft in the southwestern part of the WRSB to more than 1,750 ft along the basin trough south of the Bighorn Mountains (Johnson and others, 2007, fig. 14). Consisting substantially of fine-grained sediments, the Meeteetse Formation has been classified as a confining unit in previous studies (Richter and others, 1981; Bartos and others, 2012, plate II, and references therein), and that definition is retained herein. In many parts of the WRSB, the Meeteetse Formation is interbedded with the Lewis Shale (Bartos and others, 2012, plate II). The Lewis Shale consists primarily of shale and also is classified as a confining unit in previous studies; consequently, several previous studies combined the two lithostratigraphic units in the WRSB into a hydrogeologic unit identified as the Meeteetse-Lewis confining unit (Richter, 1981; Bartos and others, 2012, plate II). No data describing the physical characteristics of the Meeteetse confining unit in the WRSB were inventoried as part of this study.

Chemical characteristics

The chemical characteristics of groundwater from the Meeteetse confining unit in the WRSB are described using produced-water samples in this section of the report. Groundwater quality of the Meeteetse confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1; appendix H).

The chemical composition of groundwater from the Meeteetse confining unit in the WRSB was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram D). The TDS concentration (3,983 mg/L) indicated that the water was moderately saline (TDS concentration greater than or equal to

3,000 and less than or equal to 9,999 mg/L) (appendix H; appendix L, diagram D).

The available water-quality analysis was from a produced-water sample, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: chloride (sample exceeded SMCL limit of 250 mg/L), sulfate (sample exceeded SMCL of 250 mg/L), and TDS (sample exceeded SMCL limit of 500 mg/L). Characteristics and constituents measured in the produced-water sample at concentrations greater than agricultural-use standards include: SAR (sample exceeded WDEQ Class II standard of 8), chloride (sample exceeded WDEQ Class II standard of 100 mg/L), sulfate (sample exceeded WDEQ Class II standard of 200 mg/L), and TDS (sample exceeded WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

7.3.2.3 Mesaverde aquifer (Wind River structural basin)

The physical and chemical characteristics of the Mesaverde aquifer in the part of the WRSB within the NERB study area are described in this section of the report.

Physical characteristics

The Mesaverde aquifer in the WRSB consists of the water-saturated and permeable parts (members) of the Late-Cretaceous age Mesaverde Formation (Whitcomb and Lowry, 1968; Richter, 1981; Bartos and others, 2012). The Mesaverde Formation in the WRSB was defined as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9) The Mesaverde Formation consists of a variable sequence of massive to lenticular, fine-to coarse-grained sandstone, carbonaceous shale, and lesser amounts of coal (Keefer, 1972; Johnson and others, 2007, and references therein). Reported thickness of the Mesaverde Formation (including all members) is as much as 500 ft in the eastern WRSB. As many as four members of the Mesaverde Formation are recognized in the eastern WRSB—the uppermost Teapot Sandstone Member, the middle unnamed member, the Parkman Sandstone Member, and the lowermost Fales Sandstone Member (Johnson and others, 2007, and references therein). The Wallace Creek Tongue of the Cody Shale intertongues with the Mesaverde Formation and separates the Parkman and Fales Sandstone Members. 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 composing the Mesaverde aquifer (Richter, 1981; Bartos and others, 2012, 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; Bartos and others, 2012, plate II). Both of these confining units, along with the regionally extensive overlying Meeteetse-Lewis and underlying Cody confining units, create a series of confined sandstone subaquifers (Teapot Sandstone, Parkman Sandstone, and the Fales Sandstone Members) composing the Mesaverde aquifer. In some parts of the WRSB, the sandstone subaquifers may be hydraulically connected by faults and fractures in underlying and overlying confining units (Richter, 1981).

Confined conditions predominate in the Mesaverde aquifer, but unconfined (water-table) conditions are likely in outcrop areas (Richter, 1981). Permeability may be enhanced in areas where the Mesaverde aquifer is faulted and fractured (Richter, 1981). Excluding wells associated with petroleum exploration and development, few groundwater wells are installed in the Mesaverde aquifer in the WRSB, including the part of the basin within the NERB study area. No hydrogeologic data were inventoried describing the physical characteristics of the Mesaverde aquifer in the part of the WRSB within the NERB study area, but one environmental water sample and four produced-water samples were inventoried and are described below.

Chemical characteristics

The chemical characteristics of groundwater from the Mesaverde aquifer in the WRSB are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Mesaverde aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices F and H).

The chemical composition of groundwater from the Mesaverde aquifer in the WRSB was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in appendix F. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix J, diagram B). The TDS concentration (2,646 mg/L) indicated that the water was slightly saline (concentration ranging from 1,000 to 2,999 mg/L) (appendix F; appendix J, diagram B).

Several characteristics and constituents in the environmental water sample were measured at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: pH (upper SMCL limit of 8.5), TDS (USEPA SMCL of 500 mg/L), and sulfate (USEPA SMCL of 250 mg/L). Characteristics and constituents measured at concentrations greater than applicable State of Wyoming standards for agricultural use include: SAR (WDEQ Class II standard of 8), TDS (WDEQ Class II standard of 2,000 mg/L), chloride (WDEQ Class II standard of 100 mg/L), and sulfate (WDEQ Class II standard of 200 mg/L). One characteristic (pH) was measured at a value outside the range for livestock use (above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater from the Mesaverde aquifer in the WRSB also was characterized and the quality evaluated on the basis of produced-water samples from two wells. Individual constituent concentrations are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram E). TDS concentrations from the two produced-water samples (1,132 and 1,263 mg/L) indicated that waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L) (appendix H; appendix L, diagram E).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (both samples exceeded SMCL limit of 500 mg/L), pH (the one available sample exceeded upper SMCL limit of 8.5), and sulfate (the one available sample exceeded SMCL of 250 mg/L). Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (both samples exceeded WDEQ Class II standard of 8), sulfate (the one available sample exceeded WDEQ Class II standard of 200 mg/L), and pH (the one available sample exceeded upper WDEQ Class II standard of 9). One characteristic (pH) was measured at values greater than the livestock-use standard (the one available sample exceeded upper WDEQ Class III limit of 8.5).

7.3.2.4 Cody confining unit (Wind River structural basin)

The physical and chemical characteristics of the Cody confining unit in the part of the WRSB within the NERB study area are described in this section of the report.

Physical characteristics

Composed primarily of marine shale with some sandstone and siltstone, the Cody Shale in the WRSB is classified as a confining unit or leaky confining unit (Keefer, 1972; Richter, 1981; Johnson and others, 2007, and references therein; Bartos and others, 2012, plate II). The Cody Shale in the WRSB was classified as a major confining unit in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). Reported thickness of the Cody Shale is as much as 5,500 ft in the eastern WRSB (Johnson and others, 2007). Sandstones in the “upper sandy member” of the Cody Shale are important oil and gas reservoirs in the WRSB (Johnson and others, 2007). Sandstones and fractured zones of the formation may locally yield small quantities of water to groundwater wells, although poor water quality likely limits many potential uses (Richter, 1981). No wells were inventoried with hydrogeologic data describing the physical characteristics of the Cody confining unit in the part of the WRSB within the NERB study area, but chemical characteristics are described below using two produced-water samples.

Chemical characteristics

The chemical characteristics of groundwater from the Cody confining unit in the NERB study area is described using produced-water samples in this section of the report. Groundwater quality of the Cody confining unit is described in terms of a water’s suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1; appendix H).

The chemical composition of groundwater from the Cody confining unit in the WRSB was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram F). The TDS concentrations (3,625 and 5,715 mg/L) indicated that the waters were moderately saline (TDS concentrations greater than or equal to 3,000 and less than or equal to 9,999 mg/L) (appendix H; appendix L, diagram F).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (both samples exceeded SMCL limit of 500 mg/L), sulfate (both samples exceeded SMCL of 250 mg/L), and chloride (one sample exceeded SMCL limit of 250 mg/L). Characteristics and constituents measured at concentrations greater than agricultural-use standards include: TDS (both samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (both samples exceeded WDEQ Class II standard of 200 mg/L), SAR (one sample exceeded WDEQ Class II standard of 8), and chloride (one sample exceeded WDEQ Class II standard of 100 mg/L). One characteristic (TDS) was measured at a concentration greater than the livestock-use standard (one sample exceeded WDEQ Class III standard of 5,000 mg/L).

7.3.2.5 Frontier aquifer (Wind River structural basin)

The physical and chemical characteristics of the Frontier aquifer in the part of the WRSB within the NERB study area are described in this section of the report.

Physical characteristics

Water-saturated and permeable parts of the upper part of the Late Cretaceous-age Frontier Formation comprise the Frontier aquifer in the WRSB (Richter, 1981; Bartos and others, 2012, plate II). The Frontier Formation in the WRSB was classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). The Frontier Formation is composed primarily of an alternating sequence of very fine- to medium-grained sandstone and shale in three lithostratigraphic units (members)—the uppermost Wall Creek Sandstone Member, the Middle Emigrant Gap Member, and the lowermost Belle Fourche Member (Keefer, 1972; Johnson and others, 2007, and references therein). Reported thickness of the Frontier Formation (all three members) ranges from about 700 to 1,200 ft (Johnson and others, 2007, and references therein). The Wall Creek Sandstone Member and Emigrant Gap Member compose the Frontier aquifer, whereas the lowermost Belle Fourche Member composes a basal confining unit (Richter, 1981; Bartos and others, 2012, plate II). Where buried in the WRSB, the Frontier aquifer is confined from above by the thick regional Cody confining unit and below by the Mowry-Thermopolis confining unit composed of the Mowry Shale, Muddy Sandstone aquifer, and the Thermopolis Shale (Richter, 1981; Bartos and others, 2012, plate II).

Alternating layers of sandstone and shale create a series of confined sandstone subaquifers within the Frontier aquifer (Richter, 1981). Total sandstone thickness ranges from about 85 to 280 ft (Johnson and others, 1996). Sandstone beds composing the Frontier aquifer are used primarily to provide water for stock and less commonly domestic use. Water in the aquifer generally is under confined and semi-confined conditions (Whitcomb and Lowry, 1968; Richter, 1981). No wells were inventoried with hydrogeologic data describing the physical characteristics of the Frontier aquifer in the part of the WRSB within the NERB study area, but chemical characteristics of the deeply buried part of the aquifer associated with petroleum exploration and development are described below using produced-water samples.

Chemical characteristics

The chemical characteristics of groundwater from the Frontier aquifer in the WRSB are described using produced-water samples in this section of the report. Groundwater quality of the Frontier aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix H).

The chemical composition of groundwater from the Frontier aquifer in the WRSB 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 H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram G). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (5 of 11 samples, concentration ranging from 3,000 to 9,999 mg/L) to very saline (5 of 11 samples, concentration ranging from 10,000 to 34,999 mg/L), and the remaining water was slightly saline (1 of 11 samples, concentrations ranging from 1,000 to 2,999mg/L) (appendix H; appendix L, diagram G). TDS concentrations ranged from 1,161 to 22,700 mg/L, with a median of 9,734 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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.

Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 11 samples exceeded SMCL limit of 500 mg/L), iron (the one sample analyzed for this constituent exceeded the SMCL of 300 µg/L), chloride (10 of 11 samples exceeded SMCL limit of 250 mg/L), pH (1 of 3 samples below the lower SMCL limit of 6.5 and one sample above the upper SMCL limit of 8.5), and sulfate (1 of 7 samples exceeded SMCL of 250 mg/L). Several characteristics and constituents were measured in produced-water water samples from the Frontier aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 11 samples exceeded WDEQ Class II standard of 8), iron (the one sample analyzed for this constituent exceeded WDEQ Class II standard of 5,000 µg/L), TDS (10 of 11 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (10 of 11 samples exceeded WDEQ Class II standard of 100 mg/L), and sulfate (1 of 7 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (7 of 11 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (7 of 11 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (1 of 3 samples below lower WDEQ Class III limit of 6.5 and one sample above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 5 of 11 produced-water samples.

7.3.2.6 Mowry confining unit (Wind River structural basin)

The physical and chemical characteristics of the Mowry confining unit in the part of the WRSB within the NERB study area are described in this section of the report.

Physical characteristics

Because of composition consisting primarily of siliceous marine shale and bentonite, and low vertical hydraulic conductivity, the Late-Cretaceous age Mowry Shale in the WRSB is classified as a confining unit or leaky confining unit (Richter, 1981, table 4-1, and references therein; Bartos and others, 2012, plate II), and that definition is retained herein. The Mowry Shale in the WRSB was classified as a major confining unit in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). The Mowry Shale was grouped by Richter (1981) with the underlying Muddy Sandstone and Thermopolis Shale into a hydrogeologic unit identified as the Mowry-Thermopolis confining unit. Where buried in the WRSB, the Mowry-Thermopolis confining unit separates the overlying Frontier aquifer from the underlying Cloverly aquifer (Richter, 1981, table 4-1, and references therein; Bartos and others, 2012, plate II). Reported thickness of the Mowry Shale in the WRSB ranges from 395 to 560 ft (Nixon, 1973; Byers and Larson, 1979). Excluding one water sample from a well associated with petroleum exploration and development with a groundwater-quality analysis, no wells were inventoried with hydrogeologic data describing the physical and chemical characteristics of the Mowry confining unit in the part of the WRSB within the NERB study area.

Chemical characteristics

The chemical characteristics of groundwater from the Mowry confining unit in the WRSB are described using one produced-water sample in this section of the report. Groundwater quality of the Mowry confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1; appendix H).

The chemical composition of groundwater from the Mowry confining unit in the WRSB was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram H). The TDS concentration from the well (1,490 mg/L) indicated that the water was slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L).

The available water-quality analysis was from one produced-water sample, for which chemical analyses of few characteristics 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. No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) was measured at a concentration greater than the USEPA aesthetic standard for domestic use (SMCL limit of 500 mg/L). One characteristic (SAR) was greater than the State of Wyoming standard for agricultural use (WDEQ Class II standard of 8). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

7.3.3 Lower Cretaceous hydrogeologic units

Lower Cretaceous hydrogeologic units in the NERB study area are identified, and associated physical and chemical characteristics described, in this section of the report. Hydrogeologic units composing the regionally extensive Dakota (or Lower Cretaceous) aquifer system in the Northern Great Plains regional aquifer system are identified and described first, and then Lower Cretaceous hydrogeologic units not associated with the aquifer system used in the WRSB part of the NERB study area are identified and described.

7.3.3.1 Dakota aquifer system

Lithostratigraphic units of Early Cretaceous age compose a geographically extensive regional aquifer system present throughout much of the NERB study area known as the Dakota aquifer system or alternatively as the Lower Cretaceous aquifer/aquifer system (Feathers and others, 1981, fig. II-4; Downey, 1984, 1986; Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988; Busby and others, 1995; Whitehead, 1996). Confined from above by the Upper Cretaceous confining unit and below by the Jurassic-Triassic-Permian confining unit, the Dakota aquifer system consists of as many as five geologic formations (Muddy and Newcastle Sandstones, Thermopolis and Skull Creek Shales, and Cloverly Formation) and one geologic group (Inyan Kara Group) grouped into different individual hydrogeologic units named after their respective lithostratigraphic units (fig. 7-2; plates 1, 2). The physical and chemical characteristics of each of these individual hydrogeologic units are described.

7.3.3.1.1 Muddy and Newcastle aquifers

The physical and chemical characteristics of the Muddy and Newcastle aquifers in the NERB study area are described in this section of the report.

Physical characteristics

The Muddy aquifer (also known as the Muddy Sandstone aquifer) consists of the water-saturated and permeable parts of the Early Cretaceous-age Muddy Sandstone (also known as the Muddy Formation) located in the western PRSB in the NERB study area (fig. 7-2). The Muddy Sandstone present in the western PRSB is considered stratigraphically equivalent to the adjacent Newcastle Sandstone present in the eastern PRSB and adjacent Black Hills area (for example, Love and others, 1993). Geologic studies are not always consistent on the geographic extent and nomenclature for the two formations, and many studies simply consider the units equivalent and assign the Muddy Sandstone to the Newcastle Sandstone or the Newcastle Sandstone to the Muddy Sandstone because geologic characteristics generally are considered to be similar for petroleum exploration and development purposes (for example, Wulf, 1962, 1968; Stone, 1972; Berg and others, 1985; Dolson and Muller, 1994; Anna, 2010, and references therein). Because geologic characteristics are similar, the Newcastle Sandstone also is considered an aquifer in the NERB study area (fig. 7-2). In this study, the physical and chemical characteristics of the two units are described together in this section of the report, although summaries of the characteristics are presented separately because available hydrogeologic information for wells in the area inventoried as part of this study were identified by geologic formation.

The Muddy and Newcastle Sandstones are composed of marine and nonmarine very fine- to fine-grained sandstone interbedded with siltstone and mudstone/shale (Wulf, 1962, 1968; Robinson and others, 1964; Stone, 1972; Berg and others, 1985; Anna, 2010, and references therein). Thickness of the Muddy/Newcastle Sandstone ranges from 20 to 140 ft or more in the PRSB and Black Hills area (Wulf, 1962, 1968; Robinson and others, 1964; Stone, 1972; Berg and others, 1985).

Water-saturated and permeable sandstones in both formations compose the Muddy and Newcastle aquifers in the PRSB and Black Hills uplift area (Whitcomb, 1960, 1965; Johnson, 1962; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981; Berg and others, 1985). The Muddy aquifer is confined from above by the Mowry Shale (Mowry confining unit) and below by the Thermopolis Shale (Thermopolis confining unit), whereas the Newcastle aquifer is confined from above by the Mowry Shale (Mowry confining unit) and below by the Skull Creek Shale (Skull Creek confining unit) (fig. 7-2). Hydrogeologic data describing the Muddy and Newcastle aquifers in the NERB, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3. Only a few groundwater wells completed in these aquifers not associated with petroleum exploration and development were inventoried as part of this study.

In addition to being considered aquifers, the Muddy and Newcastle Sandstones compose a major petroleum reservoir in the NERB study area (Anna, 2010, and references therein). Most wells penetrating the Muddy and Newcastle Sandstones in the NERB study area were installed for petroleum exploration and development, typically at great depths necessary for petroleum generation and accumulation. Most available hydrogeologic data describing the physical and chemical characteristics of the Muddy and Newcastle aquifers are from wells associated with this exploration and development (for example, Berg and others, 1985; Smith, 1988), and these wells typically are installed at depths that are not economically feasible for other uses. In addition, groundwater from these parts of the Muddy and Newcastle aquifers are unusable because of very poor water-quality characteristics, as indicated by produced-water samples inventoried for this study and described in the following "Chemical characteristics" section; consequently, the Muddy and Newcastle aquifers are rarely used as sources of water in the NERB because of deep burial, poor water quality throughout their geographic extent, and availability of water from shallower aquifers.

Berg and others (1985) studied hydrodynamic flow in the Muddy aquifer (composed of the Muddy and Newcastle Sandstones) in the northeastern PRSB and adjacent Black Hills area to improve understanding of petroleum accumulation and migration in the aquifer/petroleum reservoir. Construction of a potentiometric-surface map using drill-stem test data indicated groundwater flows away from outcrops downdip into the PRSB with an average hydraulic gradient of 50 ft per mile. Flow patterns were interpreted to be controlled primarily by the distribution of porous sandstone, and regional patterns of groundwater flow reflected total thickness of the Muddy aquifer. Recharge was interpreted to occur in outcrop areas in the Black Hills uplift at elevations of about 4,000 ft. Local potentiometric-surface lows coincided with areas of oil accumulation. Local potentiometric-surface highs were identified and were interpreted to represent isolated areas of high pressure and downward flow from the overlying Mowry source rock (confining unit) to the Muddy aquifer. The investigators noted that although sandstones in the Muddy aquifer are lenticular and form stratigraphic traps, oil accumulations were determined largely by hydrodynamic flow and were interpreted to be in hydrodynamic equilibrium. Most oil migration and accumulation was interpreted to have occurred after uplift and exposure of the Muddy aquifer to recharge, most likely during and after the late Pliocene when the Muddy Sandstone was uplifted to present elevations.

Chemical characteristics

The chemical characteristics of the Muddy and Newcastle aquifers in the PRSB and Black Hills area in the NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Muddy and Newcastle aquifers is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

Muddy aquifer

The chemical composition of groundwater from the Muddy aquifer in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram I). The TDS concentration from the well (2,380 mg/L) indicated that the water was slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L).

Several characteristics and constituents were measured in the one environmental water sample at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (fluoride) was measured at a concentration greater than a health-based standard (USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than USEPA aesthetic standards for domestic use include: TDS (SMCL of 500 mg/L), chloride (SMCL of 250 mg/L), and fluoride (SMCL of 2 mg/L). Characteristics and constituents measured at concentrations greater than State of Wyoming standards for agricultural use include: SAR (WDEQ Class II standard of 8), TDS (Class II standard of 2,000 mg/L), boron (WDEQ Class II standard of 750 μg/L), and chloride (WDEQ Class II standard of 100 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

The chemical composition of Muddy aquifer in the NERB study area also was characterized and the quality evaluated on the basis of as many as 301 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram M). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (184 of 300 samples, concentration ranging from 10,000 to 34,999 mg/L) to moderately saline (77 of 300 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were slightly saline (25 of 300 samples, concentration ranging from 1,000 to 2,999 mg/L), fresh (8 of 300 samples, concentration less than or equal to 999 mg/L), and briny (6 of 300 samples, concentration greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram M). TDS concentrations ranged from 37 to 64,780 mg/L, with a median of 12,630 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included constituents that could be compared to health-based standards, including iron (all 21 samples exceeded the SMCL of 300 µg/L), selenium (7 of 9 samples exceeded the USEPA MCL of 50 µg/L), boron (12 of 16 samples exceeded the USEPA HAL of 6,000 µg/L), and fluoride (3 of 9 samples exceeded the USEPA MCL of 4 mg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (292 of 300 samples exceeded SMCL limit of 500 mg/L), chloride (283 of 301 samples exceeded SMCL limit of 250 mg/L), fluoride (4 of 9 samples exceeded the SMCL of 2 mg/L), sulfate (34 of 257 samples exceeded SMCL of 250 mg/L), and pH (20 of 277 samples below the lower SMCL limit of 6.5 or 20 of 277 above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in produced-water samples from the Muddy aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: boron (all 16 samples exceeded WDEQ Class II standard of 750 µg/L), selenium (all 9 samples exceeded WDEQ Class II standard of 20 µg/L), SAR (286 of 295 samples exceeded WDEQ Class II standard of 8), chloride (291 of 301 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (281 of 300 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (16 of 21 samples exceeded WDEQ Class II standard of 5,000 µg/L), sulfate (41 of 257 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (1 of 277 samples below lower WDEQ Class II limit of 4.5 and 3 of 277 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured in produced-water samples at concentrations greater than livestock-use standards include: boron (13 of 16 samples exceeded WDEQ Class III standard of 5,000 µg/L), chloride (240 of 301 samples exceeded WDEQ Class III standard of 2,000 mg/L), TDS (235 of 300 samples exceeded WDEQ Class III standard of 5,000 mg/L), selenium (7 of 9 samples exceeded WDEQ Class III standard of 50 µg/L), pH (20 of 277 samples below lower WDEQ Class III limit of 6.5 or 20 of 277 above upper WDEQ Class III limit of 8.5), and sulfate (1 of 257 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 190 of 300 produced-water samples.

Newcastle aquifer

The chemical composition of groundwater from the Newcastle aquifer in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram J). The TDS concentration from the well (8,740 mg/L) indicated that the water was moderately saline (concentration ranging from 3,000 to 9,999 mg/L).

Several characteristics and constituents were measured in the one environmental water sample at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Characteristics and constituents measured at concentrations greater than USEPA aesthetic standards for domestic use include TDS (USEPA SMCL of 500 mg/L) and chloride (USEPA SMCL of 250 mg/L). Characteristics and constituents measured at concentrations greater than applicable State of Wyoming standards for agricultural use include: SAR (WDEQ Class II standard of 8), TDS (WDEQ Class II standard of 2,000 mg/L), boron (WDEQ Class II standard of 750 µg/L), and chloride (WDEQ Class II standard of 100 mg/L). One characteristic (TDS) and two constituents (boron and chloride) were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards (WDEQ Class III standards of 5,000 mg/L, 5,000 µg/L, and 2,000 mg/L, respectively).

The chemical composition of the Newcastle aquifer in the NERB also was characterized and the quality evaluated on the basis of 163 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram N). TDS concentrations in produced-water samples were variable and indicated that most waters were very saline (74 of 163 samples, concentration ranging from 10,000 to 34,999 mg/L) to moderately saline (62 of 163 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were slightly saline (25 of 163 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (2 of 163 samples, concentration less than or equal to 999 mg/L) (appendix G–2; appendix K–2, diagram N). TDS concentrations ranged from 707 to 31,500 mg/L, with a median of 9,531 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included constituents that could be compared to health-based standards: boron (1 of 3 samples exceeded the USEPA HAL of 6,000 µg/L). Characteristics and constituents measured in produced-water samples from the Newcastle aquifer at concentrations greater than aesthetic standards for domestic use include: TDS (all 163 samples exceeded SMCL limit of 500 mg/L), iron (all 5 samples exceeded the SMCL of 300 µg/L), chloride (139 of 163 samples exceeded SMCL limit of 250 mg/L), sulfate (42 of 145 samples exceeded SMCL of 250 mg/L), and pH (2 of 151 samples below lower SMCL limit of 6.5 and 18 of 151 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in produced-water samples from the Newcastle aquifer were measured at concentrations greater than State of Wyoming standards for agricultural and livestock use in the NERB. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: boron (all 3 samples exceeded WDEQ Class II standard of 750 µg/L), selenium (the one sample exceeded WDEQ Class II standard of 20 µg/L), SAR (158 of 161 samples exceeded WDEQ Class II standard of 8), chloride (152 of 163 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (149 of 163 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (2 of 5 samples exceeded WDEQ Class II standard of 5,000 µg/L), sulfate (49 of 145 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (5 of 151 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (118 of 163 samples exceeded WDEQ Class III standard of 5,000 mg/L), boron (2 of 3 samples exceeded WDEQ Class III standard of 5,000 µg/L), chloride (103 of 163 samples exceeded WDEQ Class III standard of 2,000 mg/L), pH (2 of 151 samples below lower WDEQ Class III limit of 6.5 and 18 of 151 samples above upper WDEQ Class III limit of 8.5), and sulfate (5 of 145 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 74 of 163 produced-water samples.

7.3.3.1.2 Thermopolis and Skull Creek confining units

The physical and chemical characteristics of the Thermopolis and Skull Creek confining units in the NERB study area are described in this section of the report.

Physical characteristics

The Early Cretaceous-age Thermopolis Shale in the western PRSB and adjacent areas and the stratigraphically equivalent Skull Creek Shale in the eastern PRSB and Black Hills area consist primarily of dark gray to black marine shale, with some locally occurring thin siltstone and sandstone beds (Horn, 1955; Mapel, 1959; Robinson and others, 1964). Maximum thicknesses of the Thermopolis and Skull Creek Shales are as much as 200 and 270 ft, respectively (Horn, 1955; Mapel, 1959; Robinson and others, 1964). Previous studies in the NERB study area classified both formations as confining units, and that interpretation is retained herein (fig. 7-2; Whitcomb and others, 1958; Whitcomb, 1960, 1965; Dana, 1962; Johnson, 1962; Whitcomb and Morris, 1964; Hodson and others, 1973; Feathers and others, 1981, Stock, 1981; Lowry and others, 1986; Kyllonen and Peter, 1987). The Thermopolis and Skull Creek confining units hydraulically separate the Muddy and Newcastle aquifers from the underlying Cloverly and Inyan Kara aquifers (fig. 7-2). Few hydrogeologic data are available for the Thermopolis and Skull Creek confining units, but yield for one well completed in the Skull Creek confining unit was inventoried as part of this study (plate 3).

Chemical characteristics

The chemical characteristics of groundwater from the Skull Creek confining unit in the NERB study area is described using environmental and produced-water samples in this section of the report. Groundwater quality of the Skull Creek confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

The chemical composition of groundwater from the Skull Creek confining unit in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one spring. This sample was only analyzed for nutrients. Individual constituent concentrations are listed in appendix E–2. Nutrient constituents did not exceed applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater from the Skull Creek confining unit in the NERB study area also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram O). The TDS concentrations (12,120 and 12,870 mg/L) indicated that the waters were very saline (TDS concentrations greater than or equal to 10,000 and less than or equal to 34,999 mg/L).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One characteristic (TDS) and one constituent (chloride) were measured in both samples at concentrations greater than aesthetic standards for domestic use (SMCLs of 500 mg/L and 250 mg/L, respectively). One characteristic (pH) was measured in one sample at a value greater than the aesthetic standard for domestic use (upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in produced-water samples from the Skull Creek confining unit exceeded State of Wyoming standards for agricultural and livestock use in the NERB. Two characteristics (SAR and TDS) and one constituent (chloride) were measured in both samples at concentrations greater than agricultural-use standards (WDEQ Class II standard of 8, WDEQ Class II standard of 2,000 mg/L, and WDEQ Class II standard of 100 mg/L, respectively). One characteristic (pH) was measured in one sample at a value greater than agricultural-use standards (upper WDEQ Class II standard of 9). One characteristic (TDS) and one constituent (chloride) were measured in both samples at concentrations greater than livestock-use standards (WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L, respectively). One characteristic (pH) was measured in one sample at a value greater than livestock-use standards (upper WDEQ Class III standard of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

7.3.3.1.3 Cloverly aquifer

The physical and chemical characteristics of the Cloverly aquifer in the NERB study area are discussed in this section of the report.

Physical characteristics

Water-saturated and permeable parts of the Early Cretaceous-age Cloverly Formation compose the Cloverly aquifer (fig. 7-2). Excluding the part of the WRSB within the NERB study area, the Cloverly Formation is present in the western PRSB and adjacent eastern flank of the Bighorn Mountains and Casper arch area. Stratigraphically equivalent to the Inyan Kara Group in the eastern PRSB and Black Hills area (fig. 7-2), the Cloverly Formation consists primarily of shale and interbedded siltstone in the upper and middle parts, and persistent medium to coarse-grained, crossbedded sandstone in the lower part (Horn, 1955; Hose, 1955; Mapel, 1959; Waagé, 1959). Thickness is about 150 ft in northwestern part of the study area, and about 140 ft in the southwestern part of the study area (Horn, 1955; Hose, 1955; Mapel, 1959).

The Cloverly aquifer consists of water-saturated and permeable sandstone beds (sandstone aquifers) in the Cloverly Formation (Whitcomb, 1960, 1965; Whitcomb and others, 1966; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981). The Cloverly aquifer is confined from above by the Thermopolis confining unit and from below by the Morrison confining unit within the Jurassic-Triassic-Permian confining unit (fig. 7-2). The Statewide Wyoming Water Framework Plan classified the Cloverly Formation as a major (sandstone) aquifer in the NERB study area (WWC Engineering and others, 2007, fig. 4-9). Because the Cloverly Formation is considered a stratigraphically lateral equivalent to the Inyan Kara Group, Whitcomb (1965, p. 16) considered the Cloverly Formation to be "continuous with the Inyan Kara Group in Niobrara County as a hydrogeologic unit and to have similar water-bearing characteristics."

Excluding petroleum production, few wells are completed in the Cloverly aquifer in the NERB study area. Existing groundwater wells completed in the Cloverly aquifer are used primarily for stock purposes and less commonly non-drinking domestic purposes in areas where the formation crops out and water quality is acceptable. Use of the aquifer in the NERB study area is limited because Cloverly Formation outcrops are of small areal extent and consist of narrow bands along the eastern side of the Bighorn Mountains and the Casper arch area (plate 1). In these areas, the Cloverly Formation dips steeply, limiting the area over which the formation remains within economical well drilling depths. In addition, the few environmental water samples from wells inventoried for this study indicate groundwater in the Cloverly aquifer is slightly saline (concentration ranging from 1,000 to 2,999 mg/L) and precludes many uses without treatment.

Groundwater in the Cloverly aquifer occurs under both unconfined and confined conditions (Whitcomb, 1960, 1965; Crist and Lowry, 1972; Hodson and others, 1973; Feathers and others, 1981). Unconfined conditions typically occur in or near outcrop areas, whereas confined conditions are found in wells installed at greater depths or where the sandstone aquifers are buried by strata of overlying parts of the Cloverly Formation or other overlying lithostratigraphic units. Artesian pressure is sufficient to cause water in wells completed in the aquifer to flow in some areas. Hydrogeologic data describing the Cloverly aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Cloverly aquifer in the NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Cloverly aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

The chemical composition of groundwater from the Cloverly aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram K). TDS concentrations indicated that waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L) (appendix E–2; appendix I–2, diagram K). TDS concentrations for the wells ranged from 1,080 to 2,970 mg/L, with a median of 1,670 mg/L.

Concentrations of some characteristics and constituents in environmental water samples from the Cloverly aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (all 5 samples exceeded the SMCL of 500 mg/L), fluoride (3 of 4 samples exceeded the SMCL of 2 mg/L), sulfate (3 of 4 samples exceeded the SMCL of 250 mg/L), chloride (2 of 5 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 5 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in environmental water samples from the Cloverly aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: SAR (all 5 samples exceeded WDEQ Class II standard of 8), chloride (4 of 5 samples exceeded WDEQ Class II standard of 100 mg/L), boron (3 of 4 samples exceeded WDEQ Class II standard of 750 µg/L), sulfate (3 of 4 samples exceeded the WDEQ Class II standard of 200 mg/L), TDS (2 of 5 samples exceeded WDEQ Class II standard of 2,000 mg/L), and pH (1 of 5 samples above upper WDEQ Class II standard of 9). One characteristic (pH) was measured at a value outside the range for livestock use (1 of 5 samples above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater from the Cloverly aquifer in the the NERB study area also was characterized and the quality evaluated on the basis of 110 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram P). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (54 of 110 samples, concentration ranging from 10,000 to 34,999 mg/L) to moderately saline (39 of 110 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were slightly saline (14 of 110 samples, concentration ranging from 1,000 to 2,999 mg/L) or briny (3 of 110 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram P). TDS concentrations ranged from 1,484 to 50,760 mg/L, with a median of 11,120 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One produced-water sample included constituents that could be compared to health-based standards: boron (the one sample exceeded the USEPA HAL of 6,000 µg/L). Characteristics and constituents measured in produced-water samples from the Cloverly aquifer at concentrations greater than aesthetic standards for domestic use include: TDS (all 110 samples exceeded SMCL limit of 500 mg/L), chloride (100 of 110 samples exceeded SMCL limit of 250 mg/L), sulfate (75 of 101 samples exceeded SMCL of 250 mg/L), and pH (2 of 93 samples below the lower SMCL limit of 6.5 and 10 of 93 samples above upper SMCL limit of 8.5).

Concentrations of some characteristics and constituents measured in produced-water samples from the Cloverly aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Concentrations of characteristics and constituents measured at concentrations greater than agricultural-use standards include: SAR (all 110 samples exceeded WDEQ Class II standard of 8), boron (the one sample exceeded WDEQ Class II standard of 750 µg/L), chloride (107 of 110 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (104 of 110 samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (81 of 101 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (3 of 93 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: boron (the one sample exceeded WDEQ Class III standard of 5,000 µg/L), TDS (84 of 110 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (80 of 110 samples exceeded WDEQ Class III standard of 2,000 mg/L), pH (2 of 93 samples below lower WDEQ Class III limit of 6.5 and 10 of 93 samples above upper WDEQ Class III limit of 8.5), and sulfate (1 of 101 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 57 of 110 produced-water samples.

7.3.3.1.4 Inyan Kara aquifer

The physical and chemical characteristics of the Inyan Kara aquifer in the NERB study area are described in this section of the report.

Physical characteristics

The Inyan Kara aquifer consists of water-saturated and permeable parts of the Early Cretaceous-age Inyan Kara Group, the lowermost (oldest) Cretaceous-age lithostratigraphic unit in the Powder River structural basin and Black Hills uplift area parts of the NERB study area (fig. 7-2). Where buried and where overlying younger strata have not been wholly or partially eroded, the Inyan Kara aquifer is confined from above by the Skull Creek Shale and below by the Morrison confining unit in the Triassic-Jurassic-Permian confining unit (fig. 7-2).

Present in the central and eastern PRSB and the Black Hills area, the Inyan Kara Group is formally divided into two or three formations, depending on local geologic characteristics and investigator (some geologists interpret stratigraphy differently). The Inyan Kara Group in the central and eastern PRSB is stratigraphically equivalent to the Cloverly Formation in the western PRSB (Waagé, 1959). The uppermost formation, the Fall River Formation (also known as the Fall River Sandstone), underlies the Skull Creek Shale in many parts of the PRSB; however, the formation may be underlain by the Skull Creek Shale in some areas because of intertonguing and onlap during transgression of the sea associated with Skull Creek deposition (for example, Dolson and Muller, 1994, and references therein; Anna, 2010, fig. 15). Composed primarily of fine- to medium-grained sandstone with interbedded shale and siltstone, the Fall River Formation was deposited by a fluvio-deltaic system with many different depositional environments, including incised valley and associated channels, and delta plain/front (Waagé, 1959; Knechtel and Patterson, 1962; Robinson and others, 1964; Rasmussen and others, 1985; Dolson and Muller, 1994; Anna, 2010, and references therein). In the Black Hills area of Wyoming and South Dakota, the Fall River Formation also is informally known as the "Dakota" or "Dakota Sandstone" (Waagé, 1959; Robinson and others, 1964; Kyllonen and Peter, 1987; Dolton and others, 1990). "Dakota" is a formally recognized name for a regionally extensive lithostratigraphic unit in North and South Dakota known as the Dakota Formation/Sandstone (stratigraphically equivalent to the Muddy and Newcastle Sandstones in Wyoming).

The lowermost unit of the Inyan Kara Group, the Lakota Formation, unconformably and conformably overlies the Jurassic-age Morrison Formation and is composed of fine- to coarse-grained sandstone, conglomeratic sandstone, and variegated siltstone, mudstone, and shale; substantial lateral and vertical variations in lithology are common in the formation (Mapel and Pillmore, 1963; Robinson and others, 1964; Cuppels, 1963; Anna, 2010). The top of the Lakota Formation represents an unconformity (disconformity) that separates the unit from the overlying Fall River Formation (Robinson and others, 1964). The Lakota Formation was deposited in a fluvial/floodplain environment within valleys associated with a drainage system incised into underlying Jurassic rocks (Meyers and others, 1992; Dolson and Muller, 1994; Anna, 2010, and references therein). Both the Fall River and Lakota Formations produce oil and gas in the PRSB (Anna, 2010). Separating the two formations where present in the PRSB and possibly parts of the Black Hills uplift area is a sequence of fine-grained rocks (primarily shale) at the top of the Lakota Formation; where present, the top of this interval represents the unconformity (disconformity) between the two formations (Dolson and Muller, 1994; Anna, 2010). Where present in either PRSB or Black Hills uplift areas, some geologic studies consider this fine-grained sequence to simply be a part of the Lakota Formation, whereas other studies assigned the sequence to an additional formally recognized lithostratigraphic unit (either as member of the Lakota Formation or as a separate formation) in the Inyan Kara Group known as the Fuson Shale (for example, Waagé, 1959;

Whitcomb and Morris, 1964; Robinson and others, 1964; Gott and others, 1974; Harris, 1976; Dolson and Muller, 1994; Anna, 2010). Investigators differ as to whether the Fuson Shale is present in the Black Hills uplift, with contrasting opinions on the absence/presence of the unit in the northern or southern Black Hills uplift (see discussions of Fuson Shale in Waagé, 1959; Mapel and Pillmore, 1963; Whitcomb and Morris, 1964 Robinson and others, 1964; Gott and others, 1974; Harris, 1976). Harris (1976) concluded the Fuson Shale pinched out in the eastern edge of the central PRSB and did not continue the unit into the adjacent central Black Hills uplift. Thickness of the Inyan Kara Group in the PRSB and adjacent areas in the NERB study area ranges from about 85 to 360 ft, with an average thickness of about 160 ft (Fox and Higley, 1987e; Craddock and others, 2012).

Water-saturated and permeable sandstone beds and occasionally conglomeratic sandstone beds (collectively, sandstone aquifers) in the Fall River and Lakota Formations compose the Inyan Kara aquifer in the NERB study area (Williams, 1948; Littleton, 1950; Whitcomb and others, 1958; Whitcomb, 1960, 1965; Dana, 1962; Johnson, 1962; Whitcomb and Morris, 1964; Hodson and others, 1973; Feathers and others, 1981, Stock, 1981; Lowry and others, 1986; Kyllonen and Peter, 1987). The Statewide Wyoming Water Framework Plan classified the Inyan Kara Group (identified as the “Dakota”) in the NERB study area as a major (sandstone) aquifer (WWC Engineering and others, 2007, fig. 4-9). Physical water-bearing characteristics, including well yields, vary substantially in groundwater wells completed in the Inyan Kara aquifer (plate 3), primarily reflecting the number, thickness, and geographic extent of the sandstone beds penetrated and whether secondary permeability, such as from fractures, is present in the sandstones (Whitcomb and Morris, 1964; Hodson and others, 1973; Stock, 1981; Wyoming Groundwater, LLC, 2013). Fractures in the Inyan Kara aquifer typically are found in areas of structural deformation (folds and faults), and permeability and rates of groundwater circulation may be enhanced locally in these areas (Bowles, 1968; Stock, 1981).

The Inyan Kara aquifer is developed extensively in the Black Hills area and adjacent northeastern PRSB in Crook and Weston Counties, primarily where water of sufficient quantity and quality for domestic, stock, and less commonly public-supply use can be obtained from the large area of Inyan Kara Group outcrop surrounding the perimeter/flanks of the Black Hills uplift (plate 1) (Whitcomb and others, 1958; Whitcomb and Morris, 1964; Lowry and others, 1986; Kyllonen and Peter, 1987). Water of sufficient quantity and quality for domestic, stock, and public-supply use can be obtained from the aquifer in other parts of the NERB study area, primarily in areas where not deeply buried and drilling depths are economical. Industrial groundwater wells have been completed locally in parts of the aquifer in the NERB study area (for example, see Williams, 1948; Whitcomb, 1960, 1965). Based on the well inventory conducted for this and other studies, groundwater use from the Inyan Kara aquifer not associated with petroleum exploration and development is much greater than from other Lower Cretaceous aquifers within the NERB study area. Hydrogeologic data describing the Inyan Kara aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3.

Groundwater wells completed exclusively in either the Fall River or Lakota Formations are common, but many wells are completed in both formations to improve well yield, at least in areas where both formations are saturated and drilling depths are economical (Whitcomb and others, 1958; Whitcomb and Morris, 1964; Lowry and others, 1986; Western Water Consultants, Inc., 1996; WWC Engineering and Wyoming Groundwater, 2011; Wyoming Groundwater, LLC, 2013). Differences in the quantity and quality of water obtained from groundwater wells completed in different parts of the Inyan Kara aquifer at the same location or same general area have been noted in previous studies (for example, Williams, 1948; Whitcomb and others, 1958; Whitcomb and Morris, 1964; Stock, 1981; Lowry and others, 1986; WWC Engineering and Wyoming Groundwater, 2011; Wyoming Groundwater, LLC, 2013). Widely varying lithology contributes to the difficulty of locating water-saturated and permeable sandstone beds, especially in locations where the formation consists primarily of fine-grained rocks such as siltstone and claystone (Whitcomb and others, 1958; Whitcomb and Morris, 1964; Hodson and others, 1973; Feathers and others, 1981). Geochemical processes alter Inyan Kara aquifer water-quality characteristics as groundwater flows radially basinward away from areas of recharge along the periphery of the Black Hills (Bowles, 1968; Kyllonen and Peter, 1987).

Differences in the quality of groundwater obtained from different parts of the Inyan Kara Group (different lithostratigraphic or lithologic units) have been noted by previous investigators. Whitcomb and others (1958) noted that water from the Lakota Formation generally was softer than that from the Fall River Formation. Lowry and others (1986) reported that the Lakota Formation generally was a better aquifer than the Fall River

Formation in Weston County because many groundwater wells commonly were drilled (cased) through the Fall River Formation to obtain more consistent and larger well yields from the underlying Lakota Formation. The investigators also noted that residents of Weston County commonly reported that groundwater from the Fall River Formation generally was poorer than from the Lakota Formation. Lowry and others (1986) speculated that the differences in groundwater quality might be attributable to the different depositional environments of the two formations. Similarly, Whitcomb (1960, p. 7) noted that groundwater wells completed in the Inyan Kara Group in the vicinity of Osage in Weston County generally were cased through the Fall River Formation because of lower "artesian head" and the "popular opinion that water in the Fall River Formation is of poor quality."

A recent study examined exceedances of the arsenic MCL in groundwater from one of two public water-supply wells used to provide water to the unincorporated community of Lance Creek (WWC Engineering and Wyoming Groundwater, LLC, 2011). Both groundwater wells were determined to be open to different parts of the Inyan Kara Group, including different parts of both the Fall River and Lakota Formations with varying lithology. Samples collected from both wells indicated differences in groundwater quality, and the differences were attributed to lithologic variation in the parts of the Inyan Kara aquifer open to the wells. The investigators determined that the well with exceedances of the arsenic MCL was screened not only in parts of the Fall River and Lakota Formations, but also the intervening Fuson Shale present in the area. They concluded the arsenic in the groundwater likely was from organic-rich shale present in the Fuson Shale, but a follow-up investigation using additional drilled test wells concluded that the source of the arsenic was not only from the Fuson Shale, but also from parts of the underlying Lakota Formation (Wyoming Groundwater, LLC, 2013).

Groundwater in the Inyan Kara aquifer occurs under both unconfined and confined conditions (Whitcomb and Morris, 1964; Feathers and others, 1981; Stock, 1981; Kyllonen and Peter, 1987). In many parts of Crook County, unconfined conditions can be found in areas where water-saturated sandstone beds are present at relatively shallow depths in or near outcrop areas, but confined conditions are more common and typically are found in areas where the sandstone aquifers are buried by strata from overlying parts of the Inyan Kara Formation or other overlying lithostratigraphic units (Whitcomb and Morris, 1964; Kyllonen and Peter, 1987). Artesian pressure is sufficient to cause wells completed in the aquifer to flow, especially in topographically low areas (Whitcomb and Morris, 1964; Feathers and others, 1981; Lowry and others, 1986). Intervening fine-grained beds may locally confine sandstone beds, creating local subaquifers in the Inyan Kara Group (Stock, 1981). In a study of the hydrogeology of shallow aquifers in the vicinity of Old Woman anticline in east-central Niobrara County, Stock (1981) concluded that the Fuson Shale, where present, locally formed a leaky confining unit between the sandstone aquifers in the Lakota and Fall River Formations, a conclusion reached earlier by Johnson (1962) and subsequently assumed to be applicable to a broader area by Feathers and others (1981, fig. II-4).

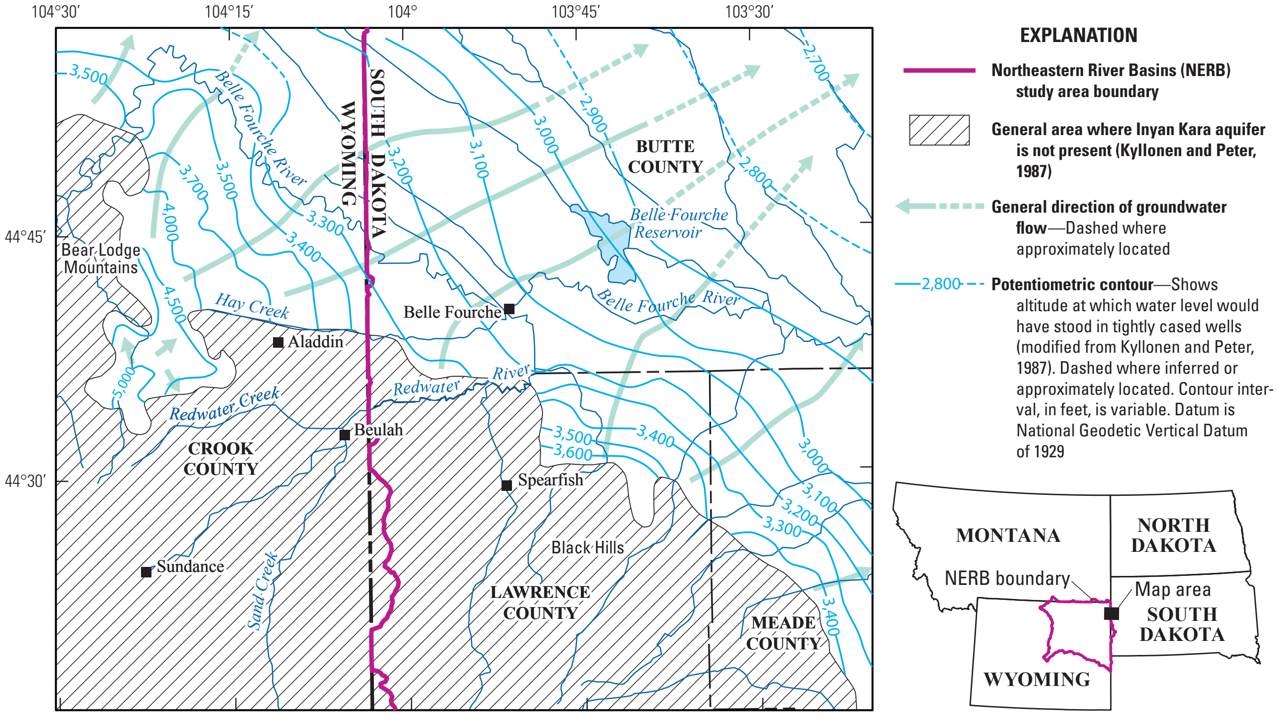
Recharge to the Inyan Kara aquifer is provided by direct infiltration and percolation of precipitation (snowmelt and rain), runoff from rain and snowmelt, and ephemeral and perennial streamflow losses on formation outcrops (Feathers and others, 1981; Stock, 1981; Kyllonen and Peter, 1987). Interformational flow also may provide recharge to the Inyan Kara aquifer in some parts of the NERB. Bowles (1968) and Gott and others (1974) hypothesized that upward movement of water from deep aquifers resulted in dissolution of anhydrite in the underlying Minnelusa Formation, resulting in development of solution collapses and breccia pipes that continue upwards into the overlying Inyan Kara Group, providing pathways through which large volumes of water under artesian pressure can recharge the Lakota and Fall River Formations at the margin of the Black Hills. Bowles (1968, p. 125) hypothesized that "subsequent flow of this ground water through channel sandstones within the Inyan Kara Group probably is most rapid in the vicinity of the Cheyenne River and larger tributaries which have eroded deeply into the overlying Skull Creek Shale" and that "in these areas, resistance to artesian discharge at the surface is at a minimum, and some groundwater probably is released either by springs or by sub-flows in streambeds and surficial materials."

Groundwater flow in the Inyan Kara aquifer has been examined locally in parts of the NERB study area. Stock (1981) constructed a potentiometric-surface map to examine groundwater flow in the Inyan Kara aquifer in the vicinity of the Old Woman anticline in the PRSB in east-central Niobrara County. The potentiometric-surface map shows groundwater flowing away from a small outcrop area and presumed source of recharge towards the east and southeast across a local monocline in the area where the investigator hypothesized it mixes with deeper waters in the aquifer. Additionally, the map shows groundwater flow deflecting around a local fault severing aquifer continuity. Large groundwater-level declines (cones of depression) are shown in the western part of the study area, and the investigator noted that these declines corresponded to areas with producing oil fields. Kyllonen and Peter (1987, fig. 7) constructed a potentiometric-surface map showing groundwater flow in the Inyan Kara aquifer in the northern Black Hills area in Wyoming (Crook County) and adjacent South Dakota (reproduced herein as fig. 7-15). The potentiometric-surface map shows groundwater generally flowing to the northeast, away and downdip from the aquifer outcrops presumed to be the source of recharge (fig. 7-15). Hydraulic gradients were reported to be much steeper near outcrops and presumed source of recharge. Furthermore, the investigators noted that that "small local groundwater-flow systems characterize the Inyan Kara aquifer near the outcrop area where water from precipitation infiltrates the aquifer, moves a short distance, and discharges at seeps and springs" (Kyllonen and Peter, 1987, p. 19). Discharge from the Inyan Kara aquifer is naturally to seeps, springs, and streams, and anthropogenically to groundwater wells (Whitcomb and Morris, 1964; Feathers and others, 1981; Stock, 1981; Kyllonen and Peter, 1987).

Chemical characteristics

The chemical characteristics of groundwater from the Inyan Kara aquifer in the NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Inyan Kara aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2).

The chemical composition of groundwater from the Inyan Kara aquifer in the NERB was characterized and the quality evaluated on the basis of environmental water samples from as many as 58 wells and one spring. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram L). TDS concentrations were variable and indicated that most waters were fresh (32 of 58 samples, concentration less than or equal to 999 mg/L) to slightly saline (25 of 58 samples, concentration ranging from 1,000 to 2,999 mg/L), and the remaining water was moderately saline (1 of 58 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–2; appendix I–2, diagram L). TDS concentrations in environmen-



Base from U.S. Geological Survey digital data, variously dated, various scales
Albers Equal-Area Conic projection
Standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

Figure 7-15. Potentiometric surface of the Inyan Kara aquifer in the northern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1960.

tal water samples from wells ranged from 180 to 3,340 mg/L, with a median of 912 mg/L.

Concentrations of some characteristics and constituents measured in environmental water samples from the Inyan Kara aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Two constituents were measured in environmental water samples at concentrations greater than health-based standards: radium-226 plus radium-228 (1 of 5 samples exceeded the USEPA MCL of 5 pCi/L) and arsenic (1 of 8 samples exceeded the USEPA MCL of 10 μg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (46 of 58 samples exceeded the SMCL of 500 mg/L), sulfate (43 of 59 samples exceeded the SMCL of 250 mg/L), iron (5 of 9 samples exceeded the SMCL of 300 μg/L), manganese (1 of 2 samples exceeded the SMCL of 50 μg/L), pH (1 of 50 samples below the lower SMCL limit of 6.5 and 5 of 50 samples above upper SMCL limit of 8.5), fluoride (2 of 46 samples exceeded the SMCL of 2 mg/L), and chloride (1 of 59 samples exceeded SMCL limit of 250 mg/L).

Concentrations of some characteristics and constituents measured in environmental water samples from the Inyan Kara aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (45 of 59 samples exceeded the WDEQ Class II standard of 200 mg/L), iron (3 of 9 samples exceeded WDEQ Class II standard of 5,000 μg/L), SAR (14 of 49 samples exceeded WDEQ Class II standard of 8), radium-226 plus radium-228 (1 of 5 samples exceeded the WDEQ Class II standard of 5 pCi/L), TDS (10 of 58 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (3 of 59 samples exceeded WDEQ Class II standard of 100 mg/L), boron (1 of 37 samples exceeded WDEQ Class II standard of 750 μg/L), and pH (1 of 50 samples below lower WDEQ Class II limit of 4.5). One constituent and one characteristic were measured at concentrations greater than or outside the range of livestock-use standards: radium-226 plus radium-228 (1 of 5 samples exceeded the WDEQ Class III standard of 5 pCi/L) and pH (1 of 50 samples below lower WDEQ Class III limit of 6.5 and 5 of 50 samples above upper WDEQ Class III limit of 8.5).

The chemical composition of Inyan Kara aquifer in the NERB also was characterized and the quality evaluated on the basis of as many as 307 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram Q). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (158 of 305 samples, concentration ranging from 1,000 to 2,999 mg/L) to moderately saline (116 of 305 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were fresh (11 of 305 samples, concentration less than or equal to 999 mg/L), very saline (19 of 305 samples, concentration ranging from 9,999 to 34,999 mg/L), and briny (1 of 305 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram Q). TDS concentrations in produced-water samples from wells ranged from 188 to 67,260 mg/L, with a median of 2,615 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Some produced-water samples included constituents that could be compared to health-based standards: selenium (the one sample exceeded the USEPA MCL of 50 μg/L) and boron (2 of 5 samples exceeded the USEPA HAL of 6,000 μg/L). Several characteristics and constituents were measured in produced-water samples at concentrations greater than aesthetic standards for domestic use: fluoride (the one sample exceeded the SMCL of 2 mg/L), TDS (304 of 305 samples exceeded SMCL limit of 500 mg/L), iron (29 of 30 samples exceeded the SMCL of 300 μg/L), sulfate (195 of 294 samples exceeded SMCL of 250 mg/L), chloride (156 of 306 samples exceeded SMCL limit of 250 mg/L), and pH (2 of 293 samples below lower SMCL limit of 6.5 and 81 of 293 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Inyan Kara aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: boron (all 5 samples exceeded WDEQ Class II standard of 750 μg/L), selenium (the one sample exceeded WDEQ Class II standard of 20 μg/L), SAR (292 of 299 samples exceeded WDEQ Class II standard of 8), chloride (217 of 306 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (206 of 294 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (204 of 305 samples exceeded WDEQ Class II standard of 2,000 mg/L), iron (18 of 30 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (15 of 293 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured in produced-water samples at concentrations greater than livestock-use standards include: selenium (the one sample exceeded WDEQ Class III standard of 50 µg/L), boron (2 of 5 samples exceeded WDEQ Class III standard of 5,000 µg/L), pH (2 of 293 samples below lower WDEQ Class III limit of 6.5 and 81 of 293 samples above upper WDEQ Class III limit of 8.5), TDS (75 of 305 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (43 of 306 samples exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate (14 of 294 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 20 of 305 produced-water samples.

7.3.3.2 Muddy aquifer (Wind River structural basin)

The physical and chemical characteristics of the Muddy aquifer in the part of the WRSB part within the NERB study area are described in this part of the report.

Physical characteristics

The Muddy aquifer (also known as the Muddy Sandstone aquifer) in the WRSB consists of the water-saturated and permeable parts of the Early-Cretaceous age Muddy Sandstone. The Muddy Sandstone is composed of massive sandstone interbedded with mudstone, and thickness ranges from 20 to 134 ft in the WRSB (Dresser, 1974). In the WRSB, the Muddy aquifer is confined from above by the Mowry Shale (Mowry confining unit) and below by the Thermopolis Shale (Thermopolis confining unit) (Bartos and others, 2012, plate II); these three hydrogeologic units in the WRSB commonly are combined into a broader hydrogeologic unit identified as the Mowry-Thermopolis confining unit (Bartos and others, 2012). Primary (intergranular) permeability in the Muddy aquifer generally is small 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 areas (Richter, 1981, p. 75). In addition to being an aquifer, the Muddy Sandstone is a major oil and gas reservoir in the WRSB. Most wells penetrating the Muddy Sandstone were installed for petroleum exploration and development, typically at great depths necessary for petroleum generation and storage. Most available hydrogeologic data describing the Muddy aquifer are from wells associated with this exploration and development, and these wells typically are installed at depths that are not economically feasible for other uses. Groundwater from these parts of the Muddy Sandstone/aquifer are unusable because of very poor water-quality characteristics, including high salinity; consequently, the Muddy aquifer is rarely used as a source of water in the WRSB because of deep burial, poor water quality throughout most of its geographic extent, and availability of water from shallower aquifers.

Excluding wells completed in relation to petroleum exploration development, few groundwater wells are installed in the Muddy aquifer in the WRSB, including the part of the aquifer within the NERB study area. Deep burial and poor water quality except near outcrops would preclude most uses of groundwater from the Muddy aquifer in the WRSB (Bartos and others, 2012; this study). Most information describing the hydrogeologic characteristics of the Muddy Sandstone in the WRSB is from oil and gas exploration and development wells. Relatively low yields, variable groundwater quality, variable hydrogeologic characteristics, and limited geographic extent preclude much aquifer development in the WRSB (Taucher and others, 2012). Little hydrogeologic data describing the physical characteristics of the Muddy aquifer in the WRSB part of the NERB were located and inventoried as part of this study, but well-yield data from one well are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Muddy aquifer in the WRSB are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Muddy aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices F and H).

The chemical composition of the Muddy aquifer in theWRSB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix F. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix J, diagram C). The TDS concentration from the well (1,690 mg/L) indicated that the water was slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L). No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) was measured at a concentration greater than the USEPA aesthetic standard for domestic use (SMCL limit of 500 mg/L). One characteristic (SAR) was measured at a value greater than the applicable State of Wyoming standard for agricultural use (WDEQ Class II standard of 8). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

The chemical composition of the Muddy aquifer in the WRSB also was characterized and the quality evaluated on the basis of as many as 14 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix H, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram I). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (6 of 14 samples, concentration ranging from 3,000 to 9,999 mg/L) to very saline (4 of 14 samples, concentration ranging from 10,000 to 34,999 mg/L) and remaining waters were slightly saline (3 of 14 samples, concentration ranging from 1,000 to 2,999 mg/L) or briny (1 of 14 samples, concentrations greater than or equal to 35,000 mg/L) (appendix H; appendix L, diagram I). TDS concentrations in produced-water samples from the Muddy aquifer ranged from 1,688 to 43,790 mg/L, with a median of 6,783 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 14 samples exceeded SMCL limit of 500 mg/L), iron (the one measured sample exceeded the SMCL limit of 300 μg/L), chloride (11 of 14 samples exceeded SMCL limit of 250 mg/L), pH (3 of 14 samples above upper SMCL limit of 8.5), and sulfate (2 of 12 samples exceeded SMCL of 250 mg/L).

Several characteristics and constituents were measured in produced-water water samples from the Muddy aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. The produced-water samples generally had concentrations of several characteristics and constituents that exceeded agricultural-use standards: SAR (all 14 samples exceeded WDEQ Class II standard of 8), iron (the one measured sample exceeded WDEQ Class II standard of 5,000 μg/L), TDS (13 of 14 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (13 of 14 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (2 of 12 samples exceeded WDEQ Class II standard of 200 mg/L), and pH (2 of 14 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured in produced-water samples from the Muddy aquifer at concentrations greater than State of Wyoming livestock-use standards include: TDS (9 of 14 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (8 of 14 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (3 of 14 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 5 of 14 produced-water samples.

7.3.3.3 Cloverly aquifer (Wind River structural basin)

The physical and chemical characteristics of the Cloverly aquifer in the part of the WRSB within the NERB study area are described in this part of the report.

Physical characteristics

Water-saturated and permeable parts of the Early-Cretaceous age Cloverly Formation compose the Cloverly aquifer in the WRSB (Bartos and others, 2012, plate II). In the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9), the Cloverly Formation in the WRSB was classified as a minor aquifer. The Cloverly aquifer in the WRSB is part of a hydrogeologic sequence identified as the “the lower and middle Mesozoic aquifers and confining units hydrogeologic sequence” (Bartos and others, 2012, plate II). The Cloverly aquifer in the WRSB is confined from above by the Thermopolis-Mowry confining unit composed of the Thermopolis and Mowry Shales and from below by the Morrison confining unit composed of the Morrison Formation (Bartos and others, 2012, plate II).

The Cloverly Formation in the WRSB consists of three informally named 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 informally named 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. Permeability in the water-saturated sandstone beds in the “Dakota and Lakota Sandstones” composing the aquifer is not only primary, but also secondary. Aquifer permeability is primarily secondary and dependent upon fracturing (Richter, 1981). Richter reported that Cloverly aquifer permeabilities were much larger in structurally deformed (folded and faulted) areas with many fractures than in relatively undeformed areas with few fractures. Excluding petroleum production, most wells in the Cloverly aquifer in the WRSB are installed for domestic or stock use in areas where the aquifer crops out and water quality is acceptable (Richter, 1981; Plafcan and others, 1995, table 16). Few groundwater wells are installed in the Cloverly aquifer parts of the WRSB within the NERB study area, and most are for stock use (Taucher and others, 2012). Few hydrogeologic data describing the physical characteristics of the Cloverly aquifer in the WRSB part of the NERB were located and inventoried as part of this study, but yield for one spring was inventoried as part of this study and is listed on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Cloverly aquifer in the WRSB part of the NERB study area are described using produced-water samples in this section of the report. Groundwater quality of the Cloverly aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendix H).

The chemical composition of groundwater from the Cloverly aquifer in the WRSB part of the NERB study area was characterized and the quality evaluated on the basis of seven produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram J). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (4 of 7 samples, concentration ranging from 3,000 to 9,999 mg/L) to slightly saline (2 of 7 samples, concentration ranging from 1,000 to 2,999 mg/L) and the remaining water was briny (1 of 7 samples, concentrations greater than or equal to 35,000 mg/L) (appendix H; appendix L, diagram J). TDS concentrations ranged from 2,158 to 44,620 mg/L, with a median of 6,460 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 7 samples exceeded SMCL limit of 500 mg/L), chloride (5 of 7 samples exceeded SMCL limit of 250 mg/L), and sulfate (4 of 7 samples exceeded SMCL of 250 mg/L). Characteristics and constituents measured in produced-water samples from the Cloverly aquifer at concentrations greater than agricultural-use standards include: SAR (all 7 samples exceeded WDEQ Class II standard of 8), TDS (all 7 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (all 7 samples exceeded WDEQ Class II standard of 100 mg/L), and sulfate (5 of 7 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (5 of 7 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (3 of 7 samples exceeded WDEQ Class III standard of 3,000 mg/L), and chloride (2 of 7 samples exceeded WDEQ Class III standard of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 1 of 7 produced-water samples.

7.3.4 Jurassic-Triassic confining unit

Hydrogeologic units composing the regionally extensive Jurassic-Triassic-Permian confining unit in the NERB study area are identified, and the physical and chemical characteristics described, in this section of the report.

Physical characteristics

Jurassic- to Permian-age lithostratigraphic units collectively compose a geographically extensive regional confining unit present throughout much of the NERB study area. Identified herein as the Jurassic-Triassic-Permian confining unit, the regional confining unit separates and hydraulically isolates overlying Lower Cretaceous and all stratigraphically younger aquifers/aquifer systems from all underlying stratigraphically older Paleozoic aquifers (fig. 7-2; Feathers and others, 1981, fig. II-4; Downey, 1984, 1986; Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988; Busby and others, 1995; Whitehead, 1996).

From stratigraphically youngest to oldest, the confining unit consists of, where present, the Jurassic-age Morrison, Sundance, and Gypsum Spring Formations; the Triassic-age Chugwater Group or Formation; Triassic- and Permian-age Spearfish and Goose Egg Formations; and the Permian-age Minnekahta Limestone and Opeche Shale (fig. 7-2; Downey, 1986; Downey and Dinwiddie, 1988). Locally, the Minnekahta Limestone and Opeche Shale are considered members of the Goose Egg Formation in some studies (Love and Christiansen, 1985; Wyoming Geological Association, 2014, and references therein). These Jurassic- to Permian-age lithostratigraphic units underlie most of the NERB study area, although the units present differ by geographic area (fig. 7-2; plate 1). The Morrison, Sundance, and Gypsum Spring Formations underlie much of the NERB, including parts of the PRSB, Black Hills area, and the eastern flank of the Bighorn Mountains. The Chugwater Group or Formation and the Goose Egg Formation are present in the western PRSB and the eastern flank of the Bighorn Mountains. The Spearfish Formation, Minnekahta Limestone, and Opeche Shale are present in the eastern PRSB and Black Hills area. Most of these units are deeply buried, except where they are present at shallow depths or crop out in small areas, primarily along the periphery of basin margins and uplifted areas (plate 1). Some of these units are very distinct and easily recognized because they contain redbeds (conspicuous red-colored sediments). Total thickness in the NERB study area ranges from 100 to 700 ft or more for Triassic lithostratigraphic units, less than 400 to 600 ft or more for Jurassic units, and 400 to 1,400 ft or more for combined Permian and underlying Pennsylvanian units (Busby and others, 1995, figs. 12–14).

Rocks composing the different lithostratigraphic units in the Jurassic-Triassic-Permian confining unit were deposited in many different nonmarine and marine environments, so lithology can vary substantially both within an individual lithostratigraphic unit and among the different lithostratigraphic units (Cavaroc and Flores, 1991, and references therein; Johnson, 1992, 1993, and references therein). The regional confining unit consists of a sequence of sandstone, siltstone, shale, carbonates (limestone and dolomite), and thin to thick deposits of evaporites (gypsum, anhydrite, and halite). Relative to total thickness of all lithologies composing the confining unit, sandstone is a very minor rock type. With the exception of sandstone, these lithologies generally have poor primary permeability or are impermeable without development of secondary permeability such as fractures (siliciclastic rocks) or solutional openings (evaporites). Permeability in the sandstones typically is primary (intergranular), but secondary permeability (fractures) is locally present (Western Water Consultants, Inc., 1983). Widely occurring interbedded evaporites/salts in several of the formations, especially the massive anhydrite and gypsum deposits in the Spearfish and Gypsum Springs Formations where intact (not dissolved by circulating groundwater), help further restrict vertical groundwater flow and contribute substantially to the confining nature of the entire unit regionally (Downey, 1986) and locally (for example, Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996).

Physical and chemical water-bearing characteristics within individual lithostratigraphic units, and among the different lithostratigraphic units of the Jurassic-Triassic-Permian confining unit, differ markedly in the NERB, primarily because of spatially variable lithology, and secondarily because of differences in cementation in siliciclastic rocks and (or) secondary porosity and permeability development in siliciclastic rocks and evaporites (Whitcomb and Morris, 1964; Crist and Lowry, 1972; Hodson and others, 1973, sheet 3; Feathers and others, 1981, fig. II-4; Downey, 1984, 1986; Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988; Busby and others, 1995; Epstein, 2001). Permeable lithologies compose little of the total thickness/volume of individual lithostratigraphic units, and thus, the confining unit. All of these characteristics result in localized permeable zones with limited vertical and geographic extent in most of the individual lithostratigraphic units composing the confining unit. Because of these highly variable water-bearing characteristics, and because permeable zones containing aquifers are localized among or within individual lithostratigraphic units, classification of the individual lithostratigraphic units within the Jurassic-Triassic-Permian confining unit as hydrogeologic/hydrostratigraphic units (aquifers, semiconfining, or confining units) differs between studies. In addition, extrapolation of local hydrogeologic characteristics to regional hydrogeologic characteristics of an individual lithostratigraphic unit further complicates classification and likely results in differing interpretations.

Parts of the lithostratigraphic units composing the Jurassic-Triassic-Permian confining unit locally are sufficiently water-saturated and permeable to contain minor local aquifers. Many of the permeable zones are minor reservoirs for hydrocarbons (oil and gas) where deeply buried (Dolton and others, 1990; Anna, 2010). In fact, the vast majority of wells completed in the Jurassic-Triassic-Permian confining unit were installed for petroleum exploration and development. Local aquifers are developed for stock or domestic use, primarily adjacent to or in structurally uplifted areas, such as the Black Hills uplift or eastern flank of the Bighorn Mountains, where they crop out or are buried at shallow depths. Most of these aquifers are contained in siliciclastic rocks such as sandstone, silty sandstone, and rarely siltstone where water-saturated and sufficiently permeable to produce usable quantities of water. In addition, local aquifers are contained in parts of formations where secondary porosity and permeability have developed in evaporites (Epstein, 2001).

Individual sandstone beds and occasional siltstone beds present in the Morrison and Sundance Formations, Chugwater Group or Formation, Spearfish Formation, and the Goose Egg Formation contain aquifers where water-saturated and permeable (Kohout, 1957; Whitcomb and others, 1958; Whitcomb and Morris, 1964; Crist and Lowry, 1972; Hodson and others, 1973; Eisen and others, 1980a, b; Feathers and others, 1981;

Western Water Consultants, Inc., 1983; Kyllonen and Peter, 1987; Epstein, 2001; Carter and others, 2002, and references therein). Groundwater wells completed in the Sundance and Spearfish Formations provide much of the water obtained from these local sandstone aquifers, as very few wells are completed in the Morrison and Goose Egg Formations and the Chugwater Group or Formation in the NERB study area. With the exception of parts of the Sundance Formation, sandstone beds containing these local aquifers generally are lenticular, discontinuous (limited geographic extent), poorly to moderately permeable, and thin relative to individual total formation and entire confining unit thickness. Some groundwater wells completed in the Sundance Formation and most wells completed in the lower part of the Spearfish Formation along the perimeter of the Black Hills uplift in Wyoming and South Dakota also yield water from parts of the formations (zones) where gypsum and anhydrite have been dissolved, increasing porosity and permeability (for example, Epstein, 2001); however, groundwater from these zones typically is saline (TDS concentrations greater than 1,000 mg/L) because of the large evaporite content in both formations that precludes many uses (Dana, 1961; Whitcomb and others, 1958; Whitcomb and Gordon, 1964; Whitcomb and Morris, 1964; Hodson and others, 1973, sheet 3; Eisen and others, 1980a, b; Lowry and others, 1986; Strobel and others, 1999; Carter and others, 2002, and references therein) (also see "Chemical characteristics" of both units described herein). Water obtained from local siliciclastic (sandstone) aquifers in the various formations composing the Triassic-Triassic-Permian confining unit commonly is saline and typically has other undesirable water-quality characteristics (see "Chemical characteristics" section below), even near outcrop areas where groundwater typically is fresher because of close proximity to recharge and shorter residence times; consequently, use of water from these aquifers in the NERB study area commonly is limited to stock or non-drinking domestic purposes.

Hydrogeologic data describing the physical characteristics of the various hydrogeologic units composing the Jurassic-Triassic-Permian confining unit in the NERB, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3. Yields to wells completed in these aquifers generally are small (generally less than 10 gal/min; plate 3) because the sandstone beds containing most of the aquifers generally are thin, commonly interbedded with finer grained rocks, and typically have limited geographic extent. Water in the aquifers typically is under unconfined conditions near outcrops and under confined conditions downdip where buried by overlying strata. In places, artesian pressure is sufficient for wells to flow or for water levels to be within a few feet of land surface (for example, Kohout, 1957; Whitcomb and Morris, 1964).

The Morrison Formation in the NERB study area has been classified as or inferred to be (1) a low-yielding aquifer (Kohout, 1957; Whitcomb and others, 1958; Whitcomb and Morris, 1964; Crist and Lowry, 1972); (2) confining unit (Whitcomb and others, 1966); (3) a confining unit with local aquifers (Hodson and others, 1973, sheet 3); (4) part of a regional confining unit with local aquifers (Feathers and others, 1981, fig. II-4, table IV-1; Kyllonen and Peter, 1987); (5) part of a regional confining unit (Downey, 1984, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995); or (6) part of a semiconfining unit in the South Dakota part of the Black Hills (Strobel and others, 1999; Carter and others, 2002, and references therein). Western Water Consultants, Inc. (1983, fig. 2) described the Morrison Formation as a sequence of "alternating leaky confining layers and secondary aquifers." The Wyoming Water Framework Plan classified the Morrison Formation in the NERB study area as a minor/marginal aquifer (WWC Engineering and others, 2007, fig. 4-9). The Morrison Formation is classified as a confining unit herein (fig. 7-2).

Although consisting substantially of fine-grained rocks such as shale, the Sundance Formation contains a member (Hulett Sandstone Member) composed primarily of fine-grained, thin- to thick-bedded sandstone and silty sandstone with shale interbeds (Rautman, 1978). Geographic extent of the Hulett Sandstone Member generally is much greater than the thin sandstone beds of localized extent present in some of the other members of the Sundance Formation. Where exposed in Crook County, the Hulett Sandstone Member ranges in thickness from about 55 to 90 ft (Whitcomb and Morris, 1964). The Hulett Sandstone Member of the Sundance Formation is considered an aquifer or potential aquifer where water-saturated and permeable (Whitcomb and others, 1958; Whitcomb and Morris, 1964; Hodson and others, 1973, sheet 3; Blankennagel and others, 1977; Feathers and others, 1981; Camp Creek Engineering, Inc., 2010). The Wyoming Water Framework Plan identified the Sundance Formation in the NERB as a marginal aquifer (WWC Engineering and others, 2007, fig. 4-9). Many of these studies identify the Hulett Sandstone Member as the Sundance aquifer, although some also include other water-saturated permeable sandstones in the formation as part of the aquifer, and that broader definition of the Sundance aquifer is retained herein. Whitcomb and Morris (1964) noted that the Hulett Sandstone Member of the Sundance Formation in parts of Crook County likely could yield more water than required for only domestic and stock purposes, and generally of better quality than the discontinuous lenticular sandstone beds present in other parts of the Sundance Formation. The Sundance aquifer is an important shallow aquifer in parts of Crook County in the Black Hills area (Dana, 1962; Whitcomb and others, 1958; Whitcomb and Morris, 1964; Hodson and others, 1973, sheet 3; Feathers and others, 1981; Camp Creek Engineering, Inc., 2010).

With the exception of the Hulett Sandstone Member of the Sundance Formation, sandstone beds in the Jurassic-Triassic-Permian confining unit containing local aquifers generally are lenticular, discontinuous (limited areal extent), poorly to moderately permeable, thin relative to individual total formation thickness, and represent most of the water-bearing strata; consequently, only small localized parts of most of these individual clastic lithostratigraphic units with sandstone (Morrison Formation, Chugwater Group or Formation, and Spearfish and Goose Egg Formations) as a whole are permeable. Studies differ as to whether these local sandstone aquifers and associated permeable zones are sufficient in number regionally (geographically) that the individual formations as a whole should be classified as aquifers throughout the NERB study area or parts of the study area. Lack of information about the water-bearing characteristics of the various formations where deeply buried, except for areas where wells have been installed for oil and gas exploration and/or development, further complicates hydrostratigraphic interpretation/classification of individual units within the Jurassic-Triassic-Permian confining unit. With the exception of parts of the Sundance Formation and the Chugwater Group or Formation that can serve as reservoirs for petroleum, lithostratigraphic units composing the confining unit generally are interpreted to be low-permeability regional seals for petroleum accumulations or potential storage of carbon dioxide (Anna, 2010, and references therein; Craddock and others, 2012, fig. 2).

Present in parts of the PRSB and Black Hills area, the Gypsum Spring Formation consists of interbedded massive white gypsum, red claystone, and thin gray, cherty limestone (Mapel and Pillmore, 1963; Robinson and others, 1964; Whitcomb and Morris, 1964; Whitcomb and others, 1966). Maximum thickness in the NERB study area ranges from 125 to 185 ft (Hodson and others, 1973, sheet 3). Where present, the Gypsum Spring Formation unconformably underlies the Sundance Formation, and unconformably overlies the Chugwater Group or Formation or Spearfish Formation (fig. 7-2; Love and others, 1993). The Gypsum Spring Formation is considered a confining unit in all studies (Whitcomb and Morris, 1964; Whitcomb and others, 1966; Feathers and others, 1981; Kyllonen and Peter, 1987; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996), including the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9), and that definition is retained herein (fig. 7-2). Although considered a confining unit, local solution cavities in or near outcrop areas of the Gypsum Spring Formation can yield small quantities of saline water with quality marginally sufficient for stock use (Hodson and others, 1973, sheet 3).

The Chugwater Group or Formation and Goose Egg Formation have been classified as or inferred to be low-yielding aquifers (Kohout, 1957; Dana, 1962; Whitcomb and Morris, 1964; Whitcomb and others, 1966; Crist and Lowry, 1972), confining units with local aquifers (Hodson and others, 1973, sheet 3), leaky confining units (Western Water Consultants, Inc., 1983), and local/regional confining units (Feathers and others, 1981, fig. II-4, table IV-1; Downey, 1984, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995). The Wyoming Water Framework Plan classified both the Chugwater Group or Formation and Goose Egg Formation as major confining units in the NERB study area (WWC Engineering and others, 2007, fig. 4-9). Both units are classified as confining units herein (fig. 7-2).

The Spearfish Formation has been classified as or inferred to be a low-yielding or minor aquifer, including in the Wyoming Water Framework Plan (Dana, 1962; Whitcomb and Gordon, 1964; Whitcomb and Morris, 1964; Hodson and others, 1973, sheet 3; Eisen and others, 1980a, b, 1981; Feathers and others, 1981; WWC Engineering and others, 2007, fig. 4-9). In the Black Hills, the Spearfish Formation in South Dakota has been classified as a confining unit in some studies that examined the unit in both Wyoming and South Dakota (Kyllonen and Peter, 1987; Strobel and others, 1999; Driscoll and others, 2002), although the lower part of the formation in the northern Black Hills functions as an aquifer due to extensive secondary porosity and permeability development (Epstein, 2001; Carter and others, 2002, and references therein). The Spearfish Formation is classified as an aquifer (Spearfish aquifer) herein (fig. 7-2) because the unit provides water to numerous wells in Crook County along the northern perimeter of the Black Hills uplift in Wyoming. However, the Spearfish Formation acts as a confining unit in much of the Black Hills, especially in South Dakota where the formation is classified as a confining unit to the Minnekahta aquifer and to other underlying Paleozoic aquifers except where it contains local aquifers of limited extent (Driscoll and others, 2002).

Where saturated and permeable, the Minnekahta Limestone is classified as a potential aquifer, aquifer, or minor aquifer in many studies (Hodson and others, 1973, sheet 3; Eisen and others, 1980a, b, 1981; Feathers and others, 1981; Strobel and others, 1999; Carter and others, 2002, and references therein). The Minnekahta Limestone is defined as an aquifer (Minnekahta aquifer) herein (fig. 7-2). The Minnekahta Limestone consists of light- to pinkish-gray, fine-grained thin-bedded limestone and dolomitic limestone (Mapel and Pillmore, 1963; Whitcomb and Morris, 1964). Maximum thickness of the Minnekahta Limestone is about 40 ft in the Black Hills uplift area (Mapel and Pillmore, 1963; Whitcomb and Morris, 1964), and thickness ranges from 20 to 40 ft in the southeastern part of the NERB (Denson and Bottinelly, 1949; Whitcomb and Morris, 1964). Some earlier studies interpreted the aquifer potential of the Minnekahta Limestone to be limited in at least parts of the NERB study area because of presumed limited well yield and poor water quality (Dana, 1961; Whitcomb and Gordon, 1964; Whitcomb and Morris, 1964). Hodson and others (1973, sheet 3) speculated that yields from groundwater wells completed in the Minnekahta Limestone could be as much as 20 gal/min, similar to yields of two wells (3 and 25 gal/min) completed in the aquifer inventoried as part of this study (plate 3). Most groundwater wells completed in the Minnekahta aquifer in the NERB study area are located in Crook County along the perimeter of the Black Hills uplift.

Present in the PRSB and Black Hills area, the Permian-age Opeche Shale conformably underlies the Minnekahta Limestone. The Opeche Shale consists of alternating beds of reddish-brown and maroon shale, silty and shaley fine-grained sandstone, and thin beds of gypsum and anhydrite (Denson and Bottinelly, 1949; Brobst and Epstein, 1963; Whitcomb and Morris, 1964). Thickness of the Opeche Shale ranges from about 70 to 120 ft in the Black Hills area (Mapel and Pillmore, 1963; Whitcomb and Morris, 1964), and from about 25 to 75 ft in the southeastern part of the NERB study area (Denson and Bottinelly, 1949; Whitcomb and Morris, 1964). Where present, the Opeche Shale conformably underlies the Minnekahta Limestone and unconformably overlies the Minnelusa Formation (fig. 7-2; Love and others, 1993). The Opeche Shale is considered a confining unit in all studies (Whitcomb and Gordon, 1964; Whitcomb and Morris, 1964; Whitcomb and others, 1966; Feathers and others, 1981; Kyllonen and Peter, 1987) and in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9), and that definition is retained herein (fig. 7-2).

Chemical characteristics

The chemical characteristics of groundwater from the different hydrogeologic units within the Permian-Triassic-Jurassic confining unit in the NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the hydrogeologic units are 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 groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–2 and G–2). Various aspects of the regional groundwater geochemistry of the Permian-Triassic-Jurassic confining unit are described in Busby and others (1995).

Morrison confining unit

The chemical composition of groundwater from the Morrison confining unit in the NERB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram M). The TDS concentration from the well (922 mg/L) indicated that the water was fresh (concentration less than or equal to 999 mg/L).

Concentrations of some characteristics and constituents in the one environmental water sample from the Morrison confining unit exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One characteristic (TDS) and one constituent (sulfate) were measured at concentrations that exceeded USEPA aesthetic standards for domestic use (SMCLs of 500 mg/L and 250 mg/L, respectively). One characteristic (SAR) and two constituents (boron and sulfate) were measured at concentrations that exceeded the applicable State of Wyoming standards for agricultural use [WDEQ Class II standards of 8 (SAR, unitless), 750 µg/L, and 200 mg/L, respectively]. No characteristics or constituents exceeded applicable State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Morrison confining unit in the NERB study area also was characterized and the quality evaluated on the basis of 20 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram R). TDS concentrations from produced-water samples were variable and indicated that most waters were very saline (10 of 20 samples, concentration ranging from 10,000 to 34,999 mg/L) to moderately saline (6 of 20 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were slightly saline (3 of 20 samples, concentration ranging from 1,000 to 2,999 mg/L) or briny (1 of 20 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–2; appendix K–2, diagram R). TDS concentrations ranged from 1,952 to 51,760 mg/L, with a median of 10,230 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples from the Morrison confining unit that exceeded aesthetic standards for domestic use include: TDS (all 20 samples exceeded SMCL limit of 500 mg/L), iron (2 of 2 samples exceeded the SMCL of 300 μg/L), sulfate (17 of 19 samples exceeded SMCL of 250 mg/L), chloride (14 of 20 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 15 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Morrison confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations that exceeded agricultural-use standards include: TDS (19 of 20 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (19 of 20 samples exceeded WDEQ Class II standard of 100 mg/L), SAR (18 of 19 samples exceeded WDEQ Class II standard of 8), and sulfate (17 of 19 samples exceeded WDEQ Class II standard of 200 mg/L). Characteristics and constituents measured at concentrations that exceeded livestock-use standards include: TDS (17 of 20 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (13 of 19 samples exceeded WDEQ Class III standard of 3,000 mg/L), chloride (7 of 20 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (1 of 15 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 11 of 20 produced-water samples.

Sundance aquifer

The chemical composition of groundwater from the Sundance aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 12 wells and three springs. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram N). TDS concentrations were variable and indicated that most waters were fresh (10 of 15 samples, concentration less than or equal to 999 mg/L) to slightly saline (4 of 15 samples, concentration ranging from 1,000 to 2,999 mg/L), the remaining water was moderately saline (1 of 15 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–2; appendix I–2, diagram N). TDS concentrations for the wells ranged from 243 to 4,100 mg/L, with a median of 847 mg/L.

Concentrations of some characteristics and constituents measured in environmental water samples from the Sundance aquifer exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (11 of 15 samples exceeded the SMCL of 500 mg/L), sulfate (10 of 15 samples exceeded the SMCL of 250 mg/L), iron (2 of 7 samples exceeded the SMCL of 300 μg/L), and pH (1 of 15 samples below the lower SMCL limit of 6.5).

Concentrations of some characteristics and constituents measured in environmental water samples from the Sundance aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB. Two characteristics and one constituent were measured in environmental water samples at concentrations greater than agricultural-use standards: mercury (one sample with analysis for mercury exceeded WDEQ Class II standard of 0.05 μg/L), sulfate (10 of 15 samples exceeded the WDEQ Class II standard of 200 mg/L), SAR (2 of 15 samples exceeded WDEQ Class II standard of 8), and TDS (1 of 15 samples exceeded WDEQ Class II standard of 2,000 mg/L). One characteristic (pH) was measured at values outside the range for livestock-use standards (1 of 15 samples below lower WDEQ Class III limit of 6.5).

The chemical composition of groundwater from the Sundance aquifer in the NERB study area also was characterized and the quality evaluated on the basis of 107 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram S). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (56 of 106 samples, concentration ranging from 3,000 to 9,999 mg/L) to very saline (42 of 106 samples, concentration ranging from 10,000 to 34,999 mg/L) and remaining waters were slightly saline (8 of 106 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix G–2; appendix K–2, diagram S). TDS concentrations ranged from 1,233 to 33,660 mg/L, with a median of 8,560 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples from the Sundance aquifer at concentrations greater than aesthetic standards for domestic use include: TDS (all 106 samples exceeded SMCL limit of 500 mg/L), sulfate (99 of 106 samples exceeded SMCL of 250 mg/L), chloride (93 of 107 samples exceeded SMCL limit of 250 mg/L), iron (1 of 3 samples exceeded the SMCL of 300 µg/L), and pH (2 of 82 samples below the lower SMCL limit of 6.5 and 8 of 82 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Sundance aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: SAR (105 of 107 samples exceeded WDEQ Class II standard of 8), TDS (103 of 106 samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (100 of 106 samples exceeded WDEQ Class II standard of 200 mg/L), chloride (99 of 107 samples exceeded WDEQ Class II standard of 100 mg/L), iron (1 of 3 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (2 of 82 samples above upper WDEQ Class II standard of 9). Two characteristics and two constituents were measured in produced-water samples at concentrations greater than livestock-use standards: TDS (92 of 106 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (51 of 106 samples exceeded WDEQ Class III standard of 3,000 mg/L), chloride (49 of 107 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (2 of 82 samples below lower WDEQ Class III limit of 6.5 and 8 of 82 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 42 of 106 produced-water samples.

Chugwater confining unit

The chemical composition of groundwater from the Chugwater confining unit in the NERB study area 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 E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram O). The TDS concentrations from the well (2,410 mg/L) and the spring (1,300 mg/L) indicated that the waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L).

Concentrations of some characteristics and constituents measured in the environmental water samples from one well completed in and one spring issuing from the Chugwater confining unit in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One characteristic (TDS) and one constituent (sulfate) were measured in water samples from both the well and spring at concentrations greater than USEPA aesthetic standards for domestic use (SMCLs of 500 mg/L and 250 mg/L, respectively). One characteristic (TDS) measured in the well sample and one constituent (sulfate) measured in both the well and spring samples exceeded the applicable State of Wyoming standards for agricultural use (WDEQ Class II standards of 2,000 mg/L and 200 mg/L, respectively). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Chugwater confining unit in the NERB also was characterized and the quality evaluated on the basis of 32 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram T). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (23 of 32 samples, concentration ranging from 1,000 to 2,999 mg/L) and remaining waters were moderately saline (8 of 32 samples, concentration ranging from 3,000 to 9,999 mg/L) to very saline (1 of 32 samples, concentration ranging from 10,000 to 34,999 mg/L) (appendix G–2; appendix K–2, diagram T). TDS concentrations ranged from 1,049 to 30,500 mg/L, with a median of 2,174 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples from the Chugwater confining unit at concentrations greater than aesthetic standards for domestic use include: TDS (all 32 samples exceeded SMCL limit of 500 mg/L), iron (the one measured sample exceeded the SMCL of 300 µg/L), sulfate (21 of 31 samples exceeded SMCL of 250 mg/L), chloride (7 of 31 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 32 samples below the lower SMCL limit of 6.5 and 6 of 32 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water water samples from the Chugwater confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: SAR (31 of 32 samples exceeded WDEQ Class II standard of 8), sulfate (26 of 31 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (17 of 32 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (16 of 31 samples exceeded WDEQ Class II standard of 100 mg/L), and pH (1 of 32 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured in produced-water samples at concentrations greater than livestock-use standards include: pH (1 of 32 samples below lower WDEQ Class III limit of 6.5 and 6 of 32 samples above upper WDEQ Class III limit of 8.5), TDS (4 of 32 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (3 of 31 samples exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate (1 of 31 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 1 of 32 produced-water samples.

Spearfish aquifer

The chemical composition of groundwater from the Spearfish aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 12 wells and one spring. Summary statistics calculated for available constituents are listed in appendix E–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–2, diagram P). TDS concentrations were variable and indicated that most waters were slightly saline (7 of 11 samples, concentration ranging from 1,000 to 2,999 mg/L) to moderately saline (2 of 11 samples, concentration ranging from 3,000 to 9,999 mg/L), and the remaining waters were fresh (1 of 11 samples, concentration less than or equal to 999 mg/L) to very saline (sample collected from spring, 30,100 mg/L, TDS concentration ranging from 10,000 to 34,999 mg/L) (appendix E–2; appendix I–2, diagram P). TDS concentrations for the 12 wells and one spring ranged from 459 to 30,100 mg/L, with a median of 2,650 mg/L (appendix E–2). Excluding the one sample collected from a spring, TDS concentrations for the wells ranged from 459 to 3,420 mg/L, with a median of 2,545 mg/L (maximum TDS and calculated median for dataset consisting only of water samples from wells not shown in appendix E–2).

Concentrations of some characteristics and constituents in water from the Spearfish aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Two constituents were measured at concentrations greater than health-based standards: strontium (all 4 samples exceeded the USEPA HAL of 4,000 µg/L) and selenium (1 of 4 samples exceeded the USEPA MCL of 50 µg/L). One characteristic and three constituents were measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use: TDS (10 of 11 samples exceeded the SMCL of 500 mg/L), sulfate (11 of 13 samples exceeded the SMCL of 250 mg/L), iron (1 of 5 samples exceeded the SMCL of 300 µg/L), and chloride [1 of 13 samples (sample collected from spring) exceeded SMCL limit of 250 mg/L].

Several characteristics and constituents were measured in the environmental water samples from the Spearfish aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Two characteristics and one constituent were measured in environmental water samples at concentrations greater than agricultural-use standards: sulfate (11 of 13 samples exceeded the WDEQ Class II standard of 200 mg/L), TDS (9 of 11 samples exceeded WDEQ Class II standard of 2,000 mg/L), selenium (3 of 4 samples exceeded WDEQ Class II standard of 20 µg/L), boron (4 of 12 samples exceeded WDEQ Class II standard of 750 µg/L), SAR [1 of 12 samples (sample collected from spring) exceeded WDEQ Class II standard of 8 (unitless)], and chloride [1 of 13 samples (sample collected from spring) exceeded WDEQ Class II standard of 100 mg/L]. One characteristic and three constituents were measured at concentrations greater than livestock-use standards: selenium (1 of 4 samples exceeded WDEQ Class III standard of 50 µg/L), TDS [1 of 11 samples (sample collected from spring) exceeded WDEQ Class III standard of 5,000 mg/L], chloride [1 of 13 samples (sample collected from spring) exceeded WDEQ Class III standard of 2,000 mg/L), and sulfate [1 of 13 samples (sample collected from spring) exceeded WDEQ Class III standard of 3,000 mg/L]. The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 1 of 11 environmental water samples (sample collected from spring).

The chemical composition of groundwater from the Spearfish aquifer in the NERB study area also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram U). The TDS concentration from the well (10,320 mg/L) indicated that the water was very saline (concentration ranging from 10,000 to 34,999 mg/L).

The available water-quality analyses were from one produced-water sample, for which chemical analyses of few characteristics 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. No constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) and two constituents (chloride and sulfate) were measured at concentrations greater than USEPA aesthetic standards for domestic use: (SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively). Two characteristics (SAR and TDS) and two constituents (chloride and sulfate) were measured at concentrations greater than State of Wyoming standards for agricultural use [WDEQ Class II standards of 8 (unitless), 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively]. One characteristic (TDS) and two constituents (chloride and sulfate) were measured at concentrations greater than State of Wyoming livestock water-quality standards (WDEQ Class III standards of 5,000 mg/L, 2,000 mg/L, and 3,000 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

Goose Egg confining unit

The chemical composition of groundwater from the Goose Egg confining unit in the NERB study area was characterized and the quality evaluated on the basis of produced-water samples from as many as seven wells. Summary statistics calculated for available constituents are listed in appendix G–2. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–2, diagram V). TDS concentrations from produced-water samples were variable and indicated that waters were moderately saline (3 of 7 samples, concentration ranging from 3,000 to 9,999 mg/L), slightly saline (2 of 7 samples, concentration ranging from 1,000 to 2,999 mg/L), and very saline (2 of 7 samples, concentration ranging from 10,000 to 34,999 mg/L) (appendix G–2; appendix K–2, diagram V). TDS concentrations ranged from 2,028 to 10,800 mg/L, with a median of 5,186 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. One characteristic and two constituents were measured at concentrations greater than aesthetic standards for domestic use: TDS (all 7 samples exceeded SMCL limit of 500 mg/L), sulfate (all 7 samples exceeded SMCL of 250 mg/L), and chloride (5 of 7 samples exceeded SMCL limit of 250 mg/L).

Several characteristics and constituents were measured in produced-water samples from the Goose Egg confining unit at concentrations greater than State of Wyoming standards for agricultural and livestock use. Concentrations of characteristics and constituents measured at concentrations greater than agricultural-use standards include: TDS (all 7 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (all 7 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (all 7 samples exceeded WDEQ Class II standard of 200 mg/L), and SAR (5 of 7 samples exceeded WDEQ Class II standard of 8). One characteristic and one constituent were measured at concentrations greater than livestock-use standards: TDS (4 of 7 samples exceeded WDEQ Class III standard of 5,000 mg/L) and sulfate (3 of 7 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 2 of 7 produced-water samples.

Minnekahta aquifer

The chemical composition of groundwater from the Minnekahta aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells and one spring. Summary statistics calculated for available constituents are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram A). TDS concentrations were variable and indicated that waters were slightly saline (5 of 7 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (2 of 7 samples, concentration less than or equal to 999 mg/L) (appendix E–3; appendix I–3, diagram A). TDS concentrations for the samples ranged from 245 to 2,200 mg/L, with a median of 1,620 mg/L.

Concentrations of some characteristics and constituents in water from the Minnekahta aquifer in the NERB study area 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: beryllium (the one uncensored sample exceeded the USEPA MCL of 4 µg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (6 of 7 samples exceeded the SMCL of 500 mg/L) and sulfate (6 of 7 samples exceeded the SMCL of 250 mg/L).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards for agricultural and livestock use in the NERB study area. One characteristic and one constituent were measured in environmental water samples at concentrations greater than agricultural-use standards: sulfate (6 of 7 samples exceeded the WDEQ Class II standard of 200 mg/L) and TDS (1 of 7 samples exceeded WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents exceeded applicable State of Wyoming livestock water-quality standards.

The chemical composition of groundwater from the Minnekahta aquifer in the NERB study area 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 G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram A). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (6 of 13 samples, concentration ranging from 3,000 to 9,999 mg/L) or briny (5 of 13 samples, concentrations greater than or equal to 35,000 mg/L). The remaining waters were slightly saline (1 of 13 samples, concentration ranging from 1,000 to 2,999 mg/L) or very saline (1 of 13 samples, concentration ranging from 10,000 to 34,999 mg/L) (appendix G–3; appendix K–3, diagram A). TDS concentrations ranged from 2,910 to 195,900 mg/L, with a median of 8,678 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in produced-water samples from the Minnekahta aquifer at concentrations greater than aesthetic standards for domestic use include: TDS (all 13 samples exceeded SMCL limit of 500 mg/L), sulfate (all 13 samples exceeded SMCL of 250 mg/L), iron (one available sample that could be compared to regulatory standard exceeded the SMCL of 300 µg/L), chloride (7 of 13 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 12 samples below the lower SMCL limit of 6.5 and 2 of 12 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Minnekahta aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: TDS (all 13 samples exceeded WDEQ Class II standard of 2,000 mg/L), sulfate (all 13 samples exceeded WDEQ Class II standard of 200 mg/L), SAR (9 of 13 samples exceeded WDEQ Class II standard of 8), iron (one available sample that could be compared to regulatory standard exceeded WDEQ Class II standard of 5,000 µg/L), and chloride (8 of 13 samples exceeded WDEQ Class II standard of 100 mg/L). Two characteristics and two constituents were measured at concentrations greater than livestock-use standards: TDS (9 of 13 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (7 of 13 samples exceeded WDEQ Class III standard of 3,000 mg/L), chloride (6 of 13 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (1 of 12 samples below lower WDEQ Class III limit of 6.5 and 2 of 12 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 6 of 13 produced-water samples.

Opeche confining unit

The chemical composition of groundwater from the Opeche confining unit in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in appendix E–3. Major ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram B). The TDS concentration from the well (602 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L). No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) was measured at a concentration greater than the USEPA aesthetic standard for domestic use (SMCL limit of 500 mg/L). One constituent (sulfate) was measured at a concentration greater than an applicable State of Wyoming standard for agricultural use (WDEQ Class II standard of 200 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming standards for livestock use.

7.4 PALEOZOIC HYDROGEOLOGIC UNITS

Paleozoic hydrogeologic units in the NERB study area consisting of sedimentary rocks ranging from Permian to Cambrian in age are identified and described in this section of the report. Paleozoic-age lithostratigraphic units composed of sedimentary rocks are shown in relation to hydrogeologic units on fig. 7-2 and plate 2.

Paleozoic hydrogeologic units (aquifers and confining units) are identified and described in this section of the report. Lithostratigraphic units consisting of sedimentary rocks of Permian, Pennsylvanian, Mississippian, Devonian, Ordovician, and Cambrian age compose the Paleozoic hydrogeologic units in the NERB study area (fig. 7-2; plates 1, 2). Paleozoic hydrogeologic units underlie Mesozoic and Cenozoic hydrogeologic units in the NERB study area, except in areas where structural deformation has uplifted and exposed the units in the various tectonic uplifts and associated geological structures bordering the mountain-basin margin of the PRSB. Depending on location, depth, and unit, wells completed in Paleozoic hydrogeologic units produce highly variable quantities and quality of water.

Paleozoic aquifers typically are most accessible in or very close to outcrop areas where they occur at shallow depths below younger hydrogeologic units. In these areas, waters generally are freshest because of recent/nearby recharge and short aquifer residence time and groundwater well drilling depths are more economical. However, permeability generally decreases and groundwater quality deteriorates relatively rapidly downgradient/downdip from outcrop areas along the structural basin margins.

Paleozoic aquifers produce water from bedrock composed primarily of carbonate rocks [for example, limestone (rock composed of the mineral calcite) and dolomite] and siliciclastic rocks (for example, sandstone) deposited primarily in marine environments. Primary porosity and intergranular permeability generally are much larger in the sandstones than in the carbonates, where primary porosity and permeability typically is very small. Carbonate aquifers generally may be utilized only in areas where substantial secondary porosity and permeability has developed. Permeability of the siliciclastic and carbonate rocks composing the Paleozoic hydrogeologic units may be substantially enhanced by fractures and (or) solution openings where the rocks have been structurally deformed by folding and faulting associated with the Laramide orogeny. In fact, development of such features in Paleozoic hydrogeologic units usually is required for siting and construction of high-yielding municipal or industrial groundwater-supply wells (Huntoon, 1993).

Porosity/permeability and groundwater circulation in Paleozoic hydrogeologic units has been studied extensively at many locations in Wyoming, and these characteristics are controlled by lithology, sedimentary structure and depositional environment, and tectonic structures such as folds and faults (for example, Lundy, 1978; Huntoon and Lundy, 1979; Thompson, 1979; Eisen and others, 1980a, b; Richter, 1981; Western Water Consultants, Inc., 1982b; Cooley, 1984, 1986; Davis, 1984; Huntoon, 1976, 1985a, b, 1993; Jarvis, 1986; Spencer, 1986; Mills, 1989; Mills and Huntoon, 1989; Wiersma, 1989; Wiersma and others, 1989; Blanchard, 1990; Blanchard and others, 1990; Younus, 1992; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Taboga, 2006). Except near outcrops, where water-table (unconfined) conditions may be encountered, groundwater in Paleozoic hydrogeologic units generally is confined.

Recharge to Paleozoic hydrogeologic units generally occurs where the units crop out, although severing by faults near recharge areas may disrupt downgradient aquifer continuity and prevent much of this recharge from entering the aquifers downgradient from outcrop areas (Lundy, 1978; Huntoon and Lundy, 1979; Thompson, 1979; Eisen and others, 1980a, b; Richter, 1981; Western Water Consultants, Inc., 1982b; Cooley, 1984, 1986; Davis, 1984; Huntoon, 1976, 1985a, b, 1993; Jarvis, 1986; Spencer, 1986; Mills, 1989; Mills and Huntoon, 1989; Wiersma, 1989; Wiersma and others, 1989; Blanchard, 1990; Blanchard and others, 1990; Younus, 1992; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Taboga, 2006). Near recharge areas, water in these hydrogeologic units can be relatively fresh and may be suitable for most uses. This is where springs typically are developed and most groundwater wells are completed. Elsewhere, and with increasing depth as the groundwater moves away from the outcrop, TDS concentrations generally increase until waters are very saline or briny, limiting the use of water for most purposes.

7.4.1 Tensleep aquifer

The physical and chemical characteristics of the Tensleep aquifer in the NERB study area are described in this section of the report.

Physical characteristics

Water-saturated and permeable parts of the Tensleep Sandstone compose the Tensleep aquifer in the NERB study area (Hodson and others, 1973; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). The Tensleep Sandstone was considered a major aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9).

Present in the western PRSB, the Pennsylvanian-age Tensleep Sandstone consists primarily of fine- to medium-grained, cross-bedded sandstone with interbedded thin dolomite beds that are more common in the lower part of the formation (Hose, 1955). The Tensleep Sandstone is unconformably overlain by the Goose Egg Formation and conformably underlain by the Amsden Formation (fig. 7-2). Where deeply buried, the Tensleep Sandstone also is an important petroleum reservoir (Dolton and others, 1990). Thickness of the Tensleep Sandstone in the NERB study area ranges from about 50 to 500 ft (Hose, 1955; Mapel, 1959; Lowry and Cummings, 1966; Crist and Lowry, 1972). The Tensleep Sandstone is deeply buried in most of the NERB study area and crops out primarily along the eastern flank of the Bighorn Mountains (plate 1), where the unit dips steeply. Most groundwater wells are completed in this area, and some can flow at rates of hundreds of gallons per minute because of high artesian pressure (Hodson and others, 1973; Western Water Consultants, Inc., 1982a, 1983). Hydrogeologic data describing the Tensleep aquifer in the NERB study area, including well-yield and spring discharge measurements and other hydraulic properties, are summarized on plate 3.

Chemical characteristics

The chemical characteristics of groundwater from the Tensleep aquifer in NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Tensleep aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–3 and G–3).

The chemical composition of groundwater from the Tensleep aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 18 wells and two springs. Summary statistics calculated for available constituents are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram C). TDS concentrations indicated that most waters were fresh (13 of 20 samples, concentrations less than or equal to 999 mg/L) to slightly saline (5 of 20 samples, concentration ranging from 1,000 to 2,999 mg/L) and the remaining waters were moderately saline (2 of 20 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–3; appendix I–3, diagram C). TDS concentrations for the wells ranged from 192 to 5,320 mg/L, with a median of 312 mg/L.

Several characteristics and constituents were measured in environmental water samples from the Tensleep aquifer at concentrations greater than applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One characteristic and two constituents were measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use: TDS (8 of 20 samples exceeded the SMCL of 500 mg/L), sulfate (7 of 19 samples exceeded the SMCL of 250 mg/L), and chloride (6 of 19 samples exceeded SMCL limit of 250 mg/L).

Several characteristics and constituents were measured in environmental water samples from the Tensleep aquifer in the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (7 of 19 samples exceeded the WDEQ Class II standard of 200 mg/L), chloride (6 of 19 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (4 of 20 samples exceeded WDEQ Class II standard of 2,000 mg/L), and SAR (1 of 19 samples exceeded WDEQ Class II standard of 8). One characteristic (TDS) was measured at concentrations greater than livestock-use standards (2 of 20 samples exceeded WDEQ Class III standard of 5,000 mg/L).

The chemical composition of groundwater from the Tensleep aquifer in the NERB study area also was characterized and the quality evaluated on the basis of 173 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram B). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (89 of 173 samples, concentration ranging from 1,000 to 2,999 mg/L) to moderately saline (71 of 173 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were very saline (12 of 173 samples, concentration ranging from 10,000 to 34,999 mg/L) to briny (1 of 173 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–3; appendix K–3, diagram B). TDS concentrations ranged from 1,138 to 41,000 mg/L, with a median of 2,962 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 173 samples exceeded SMCL limit of 500 mg/L), sulfate (165 of 173 samples exceeded SMCL of 250 mg/L), chloride (143 of 173 samples exceeded SMCL limit of 250 mg/L), iron (4 of 8 samples exceeded the SMCL of 300 µg/L), and pH (2 of 156 samples below lower SMCL limit of 6.5 and 10 of 156 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Tensleep aquifer in the NERB study area at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: chloride (168 of 173 samples exceeded WDEQ Class II standard of 100 mg/L), sulfate (168 of 173 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (151 of 173 samples exceeded WDEQ Class II standard of 2,000 mg/L), SAR (87 of 173 samples exceeded WDEQ Class II standard of 8), iron (2 of 8 samples exceeded WDEQ Class II standard of 5,000 µg/L), and pH (2 of 156 samples exceeded upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (42 of 173 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (21 of 173 samples exceeded WDEQ Class III standard of 3,000 mg/L), chloride (20 of 173 samples exceeded WDEQ Class III standard of 2,000 mg/L), and pH (2 of 156 samples below lower WDEQ Class III limit of 6.5 and 10 of 156 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 13 of 173 produced-water samples.

7.4.2 Tensleep aquifer (Wind River structural basin)

The physical and chemical characteristics of the Tensleep aquifer in the part of the WRSB within the NERB study area are discussed in this section of the report.

Physical characteristics

The Tensleep aquifer is a major aquifer in the WRSB. The Middle and Upper Pennsylvanian Tensleep Sandstone comprises the Tensleep aquifer in the WRSB (Bartos and others, 2012, 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 (Richter, 1981; Love and others, 1993). Irregular chert layers and thin limestones and dolomites also are present (Richter, 1981). Reported thickness of the hydrogeologic unit in the WRSB ranges from 200 to 600 ft (Richter, 1981, table IV-1). The aquifer is the uppermost hydrogeologic unit of the Paleozoic aquifer system and is overlain by the Phosphoria-Goose Egg aquifer and confining unit and underlain by the Amsden aquifer (Bartos and others, 2012, plate II). No regional confining unit separates the Tensleep aquifer from the underlying Amsden aquifer.

In the WRSB, the aquifer is used primarily as a source of water for domestic, public supply, industrial, and (rarely) irrigation purposes (Plafcan and others, 1995). The Tensleep aquifer is productive throughout the WRSB, and on the basis of well yields the uppermost 200 ft of the aquifer is the most productive (Richter, 1981). Hydrogeologic data compiled by Bartos and others (2012) indicated that the Tensleep aquifer is one of the most productive aquifers in the WRSB. Most wells completed in the Tensleep aquifer are located along the WRSB basin margin where the unit crops out or is buried at shallow depths. Many wells flow at land surface due to artesian pressure. Large volumes of water are withdrawn from the numerous oilfields in the basin. Permeability of the aquifer is both primary (intergranular) and secondary. Secondary porosity and permeability is common in areas of deformation (primarily fractures developed along folds), and these areas have the best potential for groundwater development (Richter, 1981; Jarvis, 1986; Spencer, 1986).

Chemical characteristics

The chemical characteristics of groundwater from the Tensleep aquifer in the WRSB are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Tensleep aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1; appendices F and H).

The chemical composition of groundwater from the Tensleep aquifer in the WRSB was characterized and the quality was evaluated on the basis of one environmental water sample. Individual constituent concentrations are listed in appendix F. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix J, diagram D). The TDS concentration from the well (248 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 1,000 mg/L). Two constituents (fluoride and iron) were measured at concentrations greater than the USEPA aesthetic standards for domestic use (SMCLs of 2 and 300 mg/L, respectively). No characteristics or constituents exceeded applicable State of

Wyoming agricultural or livestock water-quality standards.

The chemical composition of groundwater from the Tensleep aquifer in the WRSB was characterized and the quality also was evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations are listed in appendix H. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix L, diagram K). The TDS concentration from the well (2,891 mg/L) indicated that the water was slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L).

The available water-quality analysis was from one produced-water sample, for which chemical analyses of few characteristics 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. No characteristics or constituents were measured at concentrations greater than health-based standards, but one characteristic (TDS) and two constituents (chloride and sulfate) were measured at concentrations greater than the USEPA aesthetic standards for domestic use (SMCLs of 500, 250, and 250 mg/L, respectively).

Several characteristics and constituents were measured in the produced-water sample from the Tensleep aquifer at concentrations greater than State of Wyoming standards for agricultural use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: TDS (WDEQ Class II standard of 2,000 mg/L), chloride (WDEQ Class II standard of 100 mg/L), and sulfate (WDEQ Class II standard of 200 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

7.4.3 Amsden hydrogeologic unit

The physical and chemical characteristics of the Amsden hydrogeologic unit in the NERB study area are discussed in this section of the report.

Physical characteristics

Present in the northwestern PRSB and adjacent eastern flank of the Bighorn Mountains, the Amsden Formation consists of shale interbedded with cherty dolomite and limestone (Hose, 1955; Mapel, 1959). The Amsden Formation conformably underlies the Tensleep Sandstone and unconformably overlies the Madison Limestone (fig. 7-2). Thickness of the Amsden Formation is as much as 250 to 300 ft (Hose, 1955; Mapel, 1959). The water-bearing characteristics of the Amsden Formation in the NERB study area are poorly understood, and most characterization of the formation as a hydrogeologic unit is speculative. Hodson and others (1973) inferred the formation had no water-development potential. Where unfractured along the eastern flank of the Bighorn Mountains, Huntoon (1976) classified the Amsden Formation as a confining unit that hydraulically isolates the overlying Tensleep and underlying Madison aquifers. Feathers and others (1981) classified the Amsden Formation as a confining unit in the NERB study area where unfractured. Western Water Consultants, Inc. (1983, fig. 2) classified the formation as a leaky confining unit along the eastern flank of the Bighorn Mountains. The Wyoming Water Framework Plan classified the Amsden Formation as a marginal aquifer (WWC Engineering and others, 2007, fig. 4-9). Few hydrogeologic data are available for the Amsden hydrogeologic unit, but yields for two wells and one spring were inventoried as part of this study (plate 3).

Chemical characteristics

The chemical composition of the Amsden Formation in the NERB study area was characterized and the quality evaluated on the basis of seven produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram C). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (5 of 7 samples, concentration ranging from 1,000 to 2,999 mg/L), and remaining waters were moderately saline (2 of 7 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix G–3; appendix K–3, diagram C). TDS concentrations ranged from 1,964 to 3,921 mg/L, with a median of 2,538 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 7 samples exceeded SMCL limit of 500 mg/L), sulfate (all 7 samples exceeded SMCL of 250 mg/L), chloride (6 of 7 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 4 samples below lower SMCL limit of 6.5 and 1 sample above upper SMCL limit of 8.5).

Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: sulfate (all 7 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (6 of 7 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (6 of 7 samples exceeded WDEQ Class II standard of 100 mg/L), SAR (4 of 7 samples exceeded WDEQ Class II standard of 8), and pH (1 of 4 samples above upper WDEQ Class II standard of 9). One characteristic (pH) was measured at a value greater than a livestock-use standard (1 of 4 samples below lower WDEQ Class III limit of 6.5 and 1 sample above upper WDEQ Class III limit of 8.5).

7.4.4 Minnelusa aquifer

The physical and chemical characteristics of the Minnelusa aquifer in the NERB study area are described in this section of the report.

Physical characteristics

The Minnelusa aquifer in the NERB study area consists of the water-saturated and permeable parts of the Pennsylvanian- and early Permian-age Minnelusa Formation in the Black Hills uplift and adjacent eastern PRSB (plate 1; Dana, 1962; Hodson and others, 1973, and references therein; Feathers and others, 1981; Kyllonen and Peter, 1987; Strobel and others, 1999; Carter and others, 2002, and references therein). The Minnelusa Formation was classified as a minor aquifer in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). The Minnelusa aquifer is used as a source of water supply primarily for domestic and livestock wells, primarily in the Black Hills uplift area where the formation crops out or is buried at economical drilling depths (HKM Engineering and others, 2002).

The Minnelusa Formation is unconformably overlain by the Permian-age Opeche Shale and unconformably underlain by the Mississippian-age Pahasapa Limestone (fig. 7-2; DeWitt and others, 1986, 1989; Love and others, 1993). The Opeche Shale is classified as a confining unit where the Minnelusa Formation (aquifer) is saturated in Wyoming and South Dakota (fig. 7-2; Kyllonen and Peter, 1987; Strobel and others, 1999).

The Minnelusa Formation outcrop is exposed throughout much of the Black Hills uplift, most commonly at higher elevations near the Wyoming-South Dakota state line (plate 1). Where deeply buried, the Minnelusa Formation is an important petroleum reservoir (Dolton and others, 1990). In the western part of the Black Hills uplift that includes the NERB study area, reported thickness of the Minnelusa Formation ranges from 700 to 1,000 ft (DeWitt and others, 1986, fig. 4, p. 11). Lithology of the Minnelusa Formation in the eastern PRSB and Black Hills uplift of Wyoming and South Dakota varies spatially, but the lithostratigraphic unit consists most commonly of alternating sandstone and dolomite units interbedded with lesser amounts of shale and chert (DeWitt and others, 1986). Furthermore, lithology of the upper and lower parts of the Minnelusa Formation in the Black Hills uplift differs, with the upper part containing dolomite, anhydrite, eolian sandstone, siltstone, and cherty dolomite, and the lower part containing shale, dolomite, radioactive black shale, anhydrite, and sandstone (DeWitt and others, 1986, p. 35). The anhydrite beds common in the upper part of the formation commonly become solution breccias in outcrop (DeWitt and others, 1986; Epstein, 2001). Epstein (2001) also noted that gypsum (in addition to anhydrite) commonly is present in the upper part of the Minnelusa Formation in the northern Black Hills. Some investigators have noted that the gypsum and anhydrite interbedded with the sandstone is much more common in and characterizes the upper part of the Minnelusa Formation in the Black Hills uplift (DeWitt and others, 1986; Epstein, 2001). These lithologic characteristics contribute to the generally more favorable hydraulic characteristics observed for the upper rather than lower part of the Minnelusa Formation in the Black Hills uplift area (DeWitt and others, 1986; Epstein, 2001). Substantial differences in hydraulic head and groundwater quality are observed in groundwater wells completed in the upper and lower parts of the formation at many locations in the Black Hills uplift in South Dakota. These characteristics, combined with the generally more permeable and productive upper part of the formation, have led many investigators in South Dakota to generally consider the upper part of the Minnelusa Formation as an aquifer and the lower part as a confining unit; however, many of these studies also report locally permeable/productive zones in the lower part of the formation (Kyllonen and Peter, 1987; Greene, 1993; Strobel and others, 1999; Carter and others, 2002, and references therein).

Similar differences in lithology between different parts of the Minnelusa Formation in Wyoming also have led investigators to divide the formation into different hydrogeologic units. Two studies defined the upper part of the Minnelusa Formation as an aquifer and the middle part as a confining unit (Eisen and others, 1981; Feathers and others, 1981). These investigators considered the lower Minnelusa Formation a confining unit where consisting primarily of impermeable lithologies and as an aquifer where a sandstone unit known as the “Bell sand/sandstone” or “Bell Formation” is present (Foster, 1958). Presence of the Bell sandstone is highly variable and deposition was controlled by underlying Madison Limestone topography (Foster, 1958). Where water-saturated and permeable, Feathers and others (1981, table IV-1) considered the unit part of the underlying Madison aquifer.

Widely varying lithology results in highly spatially variable aquifer characteristics (plate 3). Although primary porosity and permeability in the Minnelusa Formation are present where the unit consists mainly of sandstones, substantial secondary porosity and permeability are present where the unit consists mainly of carbonate rocks (dolomite and limestone) and calcium-sulfate rocks (gypsum and anhydrite). Natural dissolution processes associated with karstification have developed or enlarged fractures and other openings in the carbonate rocks and calcium-sulfate rocks (Strobel and others, 1999; Epstein, 2001). Large well yields reported for wells completed in the Minnelusa aquifer are believed to be from these zones within the aquifer where secondary porosity and permeability have developed as a result of fractures and (or) the dissolution/solutional features. Epstein (2001, p. 31) reported that gypsum and anhydrite "comprise about 30 percent of the Minnelusa Formation" in the northern Black Hills and notes that both primarily are present in the subsurface (and more commonly in the upper part of the Minnelusa Formation) because most anhydrite at the outcrop has been removed by dissolution (except areas in Wyoming near Beulah and Sundance and some areas in South Dakota). Epstein (2001, p. 30) also noted that "calcium-sulfate rocks are much more soluble than carbonate rocks, especially where they are associated with dolomite undergoing dedolomitization, a process which results in ground water that is continuously undersaturated with respect to gypsum." In some locations in the Black Hills area, dissolution of gypsum and anhydrite in the Minnelusa aquifer has affected the hydrologic characteristics of the aquifer and hydrogeologic units above; sinkholes and other collapse features are commonly filled with breccias (Bowles and Braddock, 1963; Braddock, 1963; Epstein, 2001). Therefore, areas in the Minnelusa aquifer with calcium-sulfate rocks may be more susceptible to continuing karstic development through dissolution than areas with only carbonate rocks (dolomite and/or limestone).

Because of lithologic differences in parts of the formation (Strobel and others, 1999; Epstein, 2001), many studies in South Dakota and Wyoming divide the Minnelusa Formation in the Black Hills uplift area into different hydrogeologic units. The upper Minnelusa Formation generally is more permeable and productive than the middle part and is defined as an aquifer, whereas the middle part generally is considered to be an aquifer in the upper part and a confining unit in the lower, primarily because of differences in lithology in the upper and lower parts of the formation (Strobel and others, 1999; Epstein, 2001). It is unclear if the Minnelusa aquifer in Wyoming can be defined in a similar manner, but differences in hydraulic head observed in some studies between wells completed in the Minnelusa Formation and Madison Limestone in the study area may support this conclusion in some areas of the Black Hills within Wyoming (Bartos and others, 2002).

Recharge to the Minnelusa aquifer in Wyoming and South Dakota in the Black Hills uplift area is primarily from infiltration of precipitation on outcrops and from streamflow losses where streams cross the outcrop areas (Rahn and Gries, 1973; Kyllonen and Peter, 1987; Hortness and Driscoll, 1998; Carter and others, 2001a, b; Driscoll and Carter, 2001). Discharge from the Minnelusa aquifer in the Black Hills uplift area occurs naturally through gaining streams, springs, and vertical interaquifer leakage/flow, and anthropogenically through pumpage of groundwater from wells (Swenson, 1968a, b; Rahn and Gries, 1974; Kyllonen and Peter, 1987; Hortness and Driscoll, 1998; Carter and others, 2001a, b). Interaquifer leakage/flow from other aquifers in the Black Hills uplift area likely is very small relative to other hydrologic budget components (Carter and others, 2001a, b). Springs discharging from the Minnelusa aquifer provide flow for many streams in the Black Hills uplift area (Swenson, 1968a, b; Hortness and Driscoll, 1998; Carter and others, 2001a, b). In some areas, springs discharge near the contact of the Minnelusa and Madison aquifers.

Water budgets have been constructed for the combined Minnelusa and Madison aquifers in the Black Hills uplift area for only South Dakota and for both South Dakota and Wyoming (Carter and others, 2001a; Driscoll and Carter, 2001). A combined water budget was created because the investigators determined that most of the budget components could not be quantified individually for the two aquifers. The water budget for the combined aquifers is described in the "Madison aquifer" section herein.

Potentiometric-surface maps constructed for the Minnelusa aquifer in South Dakota (Strobel and others, 2000a; Driscoll and others, 2002) or for the Minnelusa aquifer and equivalent rocks in Wyoming, South Dakota, and Montana (Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988, fig. 19, p. A23; Bartos and others, 2002) show that groundwater in the Minnelusa aquifer in Wyoming and South Dakota in the vicinity of the

Black Hills generally flows radially outward from the Minnelusa Formation outcrops that encircle the central part of the uplift composed of igneous and metamorphic rocks. Several of these maps (Williamson and others, 2000; Bartos and others, 2002; Driscoll and others, 2002) are reproduced herein as figure 7-16. A more detailed potentiometric-surface map of the Minnelusa aquifer in the northwestern Black Hills uplift area in Wyoming and South Dakota constructed by Kyllonen and Peter (1987) is reproduced herein as figure 7-17. In the vicinity of the Bear Lodge Mountains, groundwater in the Minnelusa aquifer primarily flows to the east. The location of outcrop areas, in combination with higher precipitation in upland areas and radial groundwater flow away from these areas, indicates the primary sources of recharge to the Minnelusa aquifer are precipitation on outcrops and streamflow losses where streams cross outcrops.

Chemical characteristics

The chemical characteristics of groundwater from the Minnelusa aquifer in NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Minnelusa aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–3 and G–3).

Environmental water samples

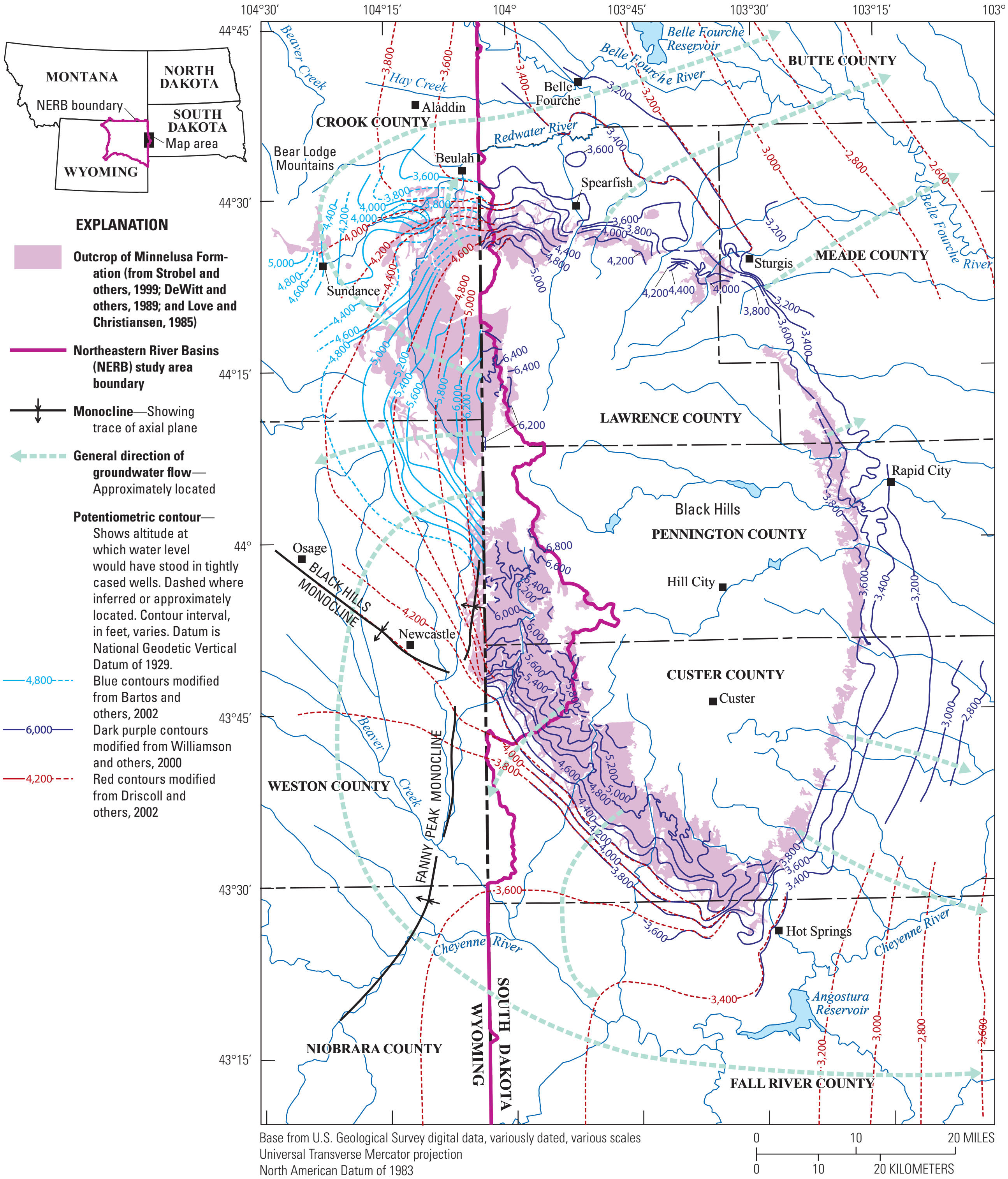
The chemical composition of the Minnelusa aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 32 wells and one spring. Summary statistics calculated for available constituents are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram D). TDS concentrations indicated that most waters were fresh (19 of 33 samples, concentrations less than or equal to 999 mg/L) to slightly saline (13 of 33 samples, concentration ranging from 1,000 to 2,999 mg/L) and the remaining water was moderately saline (1 of 33 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–3; appendix I–3, diagram D). TDS concentrations for the wells ranged from 218 to 3,220 mg/L, with a median of 551 mg/L.

Concentrations of some characteristics and constituents in water from Minnelusa aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Constituents measured at concentrations greater than health-based standards include: beryllium (3 of 5 samples analyzed for beryllium listed in appendix E–3 could be compared to the regulatory standard, whereas the remaining 2 samples were censored at a concentration greater than the regulatory standard; of these 3 samples, one exceeded the USEPA MCL of 4 μg/L) and molybdenum (1 of 5 samples exceeded the USEPA HAL of 40 μg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (19 of 33 samples exceeded the SMCL of 500 mg/L), sulfate (16 of 33 samples exceeded the SMCL of 250 mg/L), manganese (2 of 7 samples exceeded the SMCL of 50 μg/L), iron (1 of 9 samples exceeded the SMCL of 300 μg/L), fluoride (1 of 29 samples exceeded the SMCL of 2 mg/L), and chloride (1 of 33 samples exceeded SMCL limit of 250 mg/L).

Several characteristics and constituents were measured at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (18 of 33 samples exceeded the WDEQ Class II standard of 200 mg/L), TDS (7 of 33 samples exceeded WDEQ Class II standard of 2,000 mg/L), manganese (1 of 7 samples exceeded WDEQ Class II standard of 200 μg/L), iron (1 of 9 samples exceeded the WDEQ Class II standard of 5,000 μg/L), SAR (2 of 33 samples exceeded WDEQ Class II standard of 8), and chloride (1 of 33 samples exceeded WDEQ Class II standard of 100 mg/L). No characteristics or constituents were measured at concentrations greater than applicable State of Wyoming livestock water-quality standards.

Produced-water samples

The chemical composition of groundwater from the Minnelusa aquifer in the NERB study area also was characterized and the quality evaluated on the basis of 929 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram D). TDS concentrations from produced-water samples were variable and indicated that waters were briny (325 of 928 samples, concentrations greater than or equal to 35,000 mg/L), moderately saline (284 of 928 samples, concentration ranging from 3,000 to 9,999 mg/L), very saline (211 of 928 samples, concentration ranging from 10,000 to 34,999 mg/L), and slightly saline (104 of 928 samples, concentration ranging from 1,000 to 2,999 mg/L) to fresh (4 of 928 samples, concentrations less than or equal to 999 mg/L) (appendix G–3; appendix K–3, diagram D). TDS concentrations ranged from 91.9 to 307,700 mg/L, with a median of 15,250 mg/L.



Base from U.S. Geological Survey digital data, variously dated, various scales
Universal Transverse Mercator projection
North American Datum of 1983

Figure 7-16. Potentiometric surfaces of the Minnelusa aquifer in the Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota.

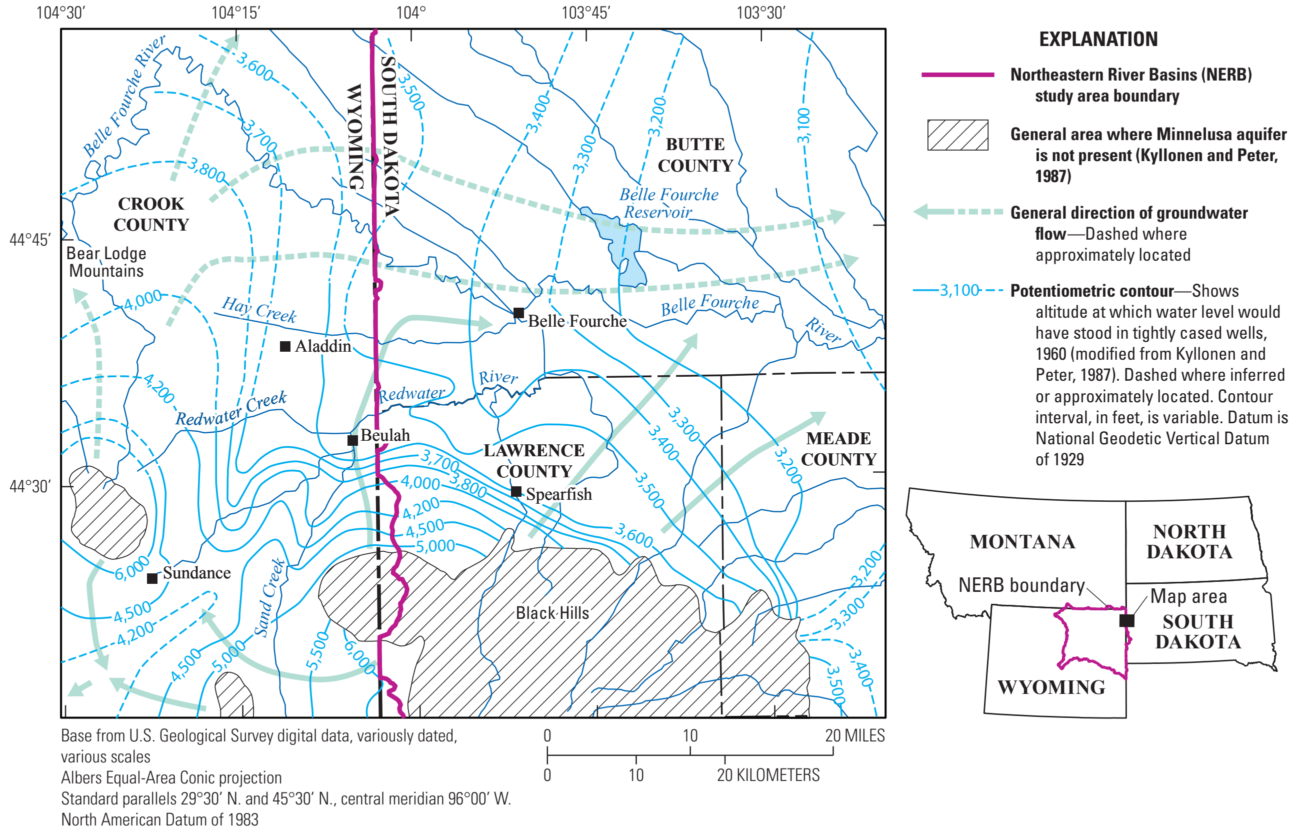


Figure 7-17. Potentiometric surface of the Minnelusa aquifer in the northwestern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1960.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Groundwater-quality analyses from several produced-water samples included constituents that could be compared to health-based standards: selenium (6 of 7 samples exceeded the USEPA MCL of 50 μg/L) and boron (7 of 11 samples exceeded the USEPA HAL of 6,000 μg/L). Characteristics and constituents measured in produced-water samples at concentrations greater than aesthetic standards for domestic use include: TDS (926 of 928 samples exceeded SMCL limit of 500 mg/L), sulfate (909 of 927 samples exceeded SMCL of 250 mg/L), iron (110 of 131 samples exceeded the SMCL of 300 μg/L), chloride (757 of 927 samples exceeded SMCL limit of 250 mg/L), and pH (100 of 861 samples below lower SMCL limit of 6.5 and 29 of 861 samples above upper SMCL limit of 8.5). One constituent (fluoride) was measured at a concentration equal to the aesthetic standard for domestic use (1 of 2 samples at the SMCL of 2 mg/L).

Several characteristics and constituents were measured in produced-water samples from the Minnelusa aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: boron (all 11 samples exceeded WDEQ Class II standard of 750 μg/L), sulfate (913 of 927 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (908 of 928 samples exceeded WDEQ Class II standard of 2,000 mg/L), selenium (6 of 7 samples exceeded WDEQ Class II standard of 20 μg/L), SAR (748 of 929 samples exceeded WDEQ Class II standard of 8), chloride (834 of 927 samples exceeded WDEQ Class II standard of 100 mg/L), iron (50 of 131 samples exceeded WDEQ Class II standard of 5,000 μg/L), and pH (2 of 861 samples below lower WDEQ Class II limit of 4.5 and 16 of 861 samples above upper WDEQ Class II standard of 8.5). Characteristics and constituents measured at concentrations greater than livestock-use standards include: selenium (6 of 7 samples exceeded WDEQ Class III standard of 50 μg/L), boron (8 of 11 samples exceeded WDEQ Class III standard of 5,000 μg/L), TDS (668 of 928 samples exceeded WDEQ Class III standard of

5,000 mg/L), chloride (558 of 927 samples exceeded WDEQ Class III standard of 2,000 mg/L), sulfate (392 of 927 samples exceeded WDEQ Class III standard of 3,000 mg/L), and pH (100 of 861 samples below lower WDEQ Class III limit of 6.5 and 29 of 861 samples above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 536 of 928 produced-water samples.

7.4.5 Hartville aquifer (Hartville uplift area)

The physical and chemical characteristics of the Hartville aquifer in the NERB study area are described in this section of the report.

Physical characteristics

The Hartville aquifer consists of water-saturated and permeable parts of the Late Mississippian-, Pennsylvanian-, and Permian-age Hartville Formation in the Hartville uplift (Bartos and others, 2013, plate K, and references therein). The Hartville Formation is present only in the small part of Hartville uplift within the NERB study area (plate 1). The Hartville aquifer is used as a source of water for stock, domestic, public-supply, and irrigation purposes, primarily south of the NERB study area; much of the aquifer development is located within and near the town of Glendo (Morrison-Maierle, Inc., 1984; Hibsman and Associates, 1990; Wyoming Groundwater, LLC, 2009).

The Hartville Formation is composed of carbonate rocks (limestone and dolomite), sandstone, shale, siltstone, and breccias; sandstones commonly are cherty and dolomitic (Condra and Reed, 1935; Condra and others, 1940; Love and others, 1953; Bates, 1955; Rapp and others, 1957; Morris and Babcock, 1960; Hoyt, 1962; Welder and Weeks, 1965; Sando and Sandberg, 1987; Wyoming Groundwater, LLC, 2009). Thickness varies by location, but maximum reported thickness is as much as 1,225 ft (Condra and Reed, 1935; Condra and others, 1940; Love and others, 1953; Bates, 1955; Rapp and others, 1957; Morris and Babcock, 1960; Hoyt, 1962; Welder and Weeks, 1965; Libra and others, 1981; Wyoming Groundwater, LLC, 2009). The Hartville Formation has been divided into many smaller lithostratigraphic units/intervals by different investigators (Condra and Reed, 1935; Condra and others, 1940; Love and others, 1953; Bates, 1955; Hoyt, 1962; Welder and Weeks, 1965; Mallory, 1967; Sando and Sandberg, 1987).

The Hartville aquifer is confined from above by the Opeche and Goose Egg confining units and underlain by the Guernsey aquifer (Bartos and others, 2012, plate K). In areas where overlying Paleozoic and Mesozoic rocks have been eroded, the Tertiary-age White River hydrogeologic unit directly overlies the Hartville aquifer (Welder and Weeks, 1965; Wyoming Groundwater, LLC, 2009). Many studies consider the Hartville aquifer to be part of a regional Paleozoic aquifer system where hydraulically connected to underlying and overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation (Eisen and others, 1980a; Libra and others, 1981; Western Water Consultants, Inc., 1982b).

Sandstones are the most productive zones within the Hartville aquifer (Rapp and others, 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Libra and others, 1981; Wyoming Groundwater, LLC, 2009). Most groundwater wells are completed in a productive white to yellow, fine- to medium-grained, subangular to subrounded sandstone 100-ft thick or more present near the top of the unit known informally as the "Converse sand" (Rapp and others, 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen and others, 1980a; Libra and others, 1981; Western Water Consultants, Inc., 1982b; Wyoming Groundwater, LLC, 2009). In addition to intergranular permeability, fractures reportedly increase Converse sand permeability in some areas (Wyoming Groundwater, LLC, 2009). Carbonate intervals within the Hartville aquifer generally are not productive or are much less productive than sandstones, but brittle carbonates in areas with secondary porosity and permeability ("interconnected fractures, cavities, and solution-enhanced features") may be productive (Wyoming Groundwater, LLC, 2009, p. 4-8). Intervals with secondary porosity and permeability development may be more common in breccias within the Hartville aquifer (Wyoming Groundwater, LLC, 2009). Groundwater wells completed in the Converse sand commonly are artesian (Rapp and others, 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen and others, 1980a; Libra and others, 1981; Western Water Consultants, Inc., 1982b; Wyoming Groundwater, LLC, 2009). Most hydrogeologic data describing the Hartville aquifer are from areas immediately south of the NERB study area, but one well-yield measurement (104 gal/min) was inventoried (plate 3).

Recharge to the Hartville aquifer in the Glendo area is from losing streams, overlying hydrogeologic units, and precipitation on outcrops (Welder and Weeks, 1965; Wyoming Groundwater, LLC, 2009). Discharge is to overlying hydrogeologic units and to various groundwater wells completed in the aquifer, many of which are completed in the Converse sand.

Chemical characteristics

The chemical characteristics of groundwater from the Hartville aquifer in NERB study area are described using environmental water samples in this section of the report. Groundwater quality of the Hartville aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (appendix E–3; table 5-1).

The chemical composition of Hartville aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations for available constituents are listed in appendix E–3, and major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram E). TDS concentrations measured in water from both wells (256 and 305 mg/L) indicate that waters are fresh (TDS concentrations less than or equal to 999 mg/L) (appendix E–3; appendix I–3, diagram E).

Concentrations of some characteristics and constituents in water from wells completed in the Hartville aquifer exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. One constituent (gross-alpha radioactivity) was measured in one of two samples at an activity greater than a USEPA health-based standard (USEPA MCL of 15 pCi/L) and State of Wyoming domestic, agriculture, and livestock water-quality standards (WDEQ Class I, II, and III standards of 15 pCi/L). One constituent (fluoride) was measured in one of two water samples at a concentration greater than the aesthetic standard for domestic use (SMCL of 2 mg/L).

7.4.6 Madison aquifer

The physical and chemical characteristics of the Madison aquifer in the NERB study area are described in this section of the report.

Physical characteristics

The Madison aquifer in the NERB study area consists of the water-saturated and permeable parts of the Mississippian-age Madison Limestone in the western PRSB and eastern flanks of the Bighorn Mountains and the stratigraphically equivalent Mississippian-age Pahasapa Limestone in the Black Hills uplift and adjacent eastern PRSB (fig. 7-2; Dana, 1962; Hodson and others, 1973, and references therein; Wyoming State Engineer's Office, 1974; Old West Regional Commission, 1976; Swenson and others, 1976; Woodward-Clyde Consultants, 1980; Feathers and others, 1981; Downey, 1984, 1986; Kyllonen and Peter, 1987; Downey and Dinwiddie, 1988; Whitehead, 1996). Both the Madison and Pahasapa Limestones are classified as major aquifers in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). The Madison Limestone crops out along the eastern flank of the Bighorn Mountains and along the Laramie Mountains immediately south of the NERB study area (plate 1). Most of the outcrop area for the Pahasapa Limestone in the Black Hills uplift area is located in South Dakota (fig. 7-18; plate 1; DeWitt and others, 1989; Strobel and others, 1999). The Madison aquifer is a major regional aquifer of the Northern Great Plains regional aquifer system, and geographic area extends far beyond the NERB study area in Wyoming into parts of Montana and North and South Dakota (Downey, 1984, 1986; Downey and Dinwiddie, 1988; Whitehead, 1996).

Numerous wells completed in the Madison aquifer in the NERB study area provide water for stock, domestic, agricultural/irrigation, industrial (primarily water flooding/secondary oil recovery), and public-supply purposes (Feathers and others, 1981; Wyoming State Engineer's Office, 1993; HKM Engineering, Inc., and others, 2002a, b). With the exception of industrial wells installed to provide water for secondary oil recovery, most groundwater wells are completed in and along the uplift areas where the Madison aquifer is exposed or is buried at shallow depths, waters are freshest, and wells can be completed at economical depths. Downdip and away from uplifted areas where the aquifer is exposed or is buried at shallow depths, drilling depths are uneconomical for most uses and groundwater quality decreases as aquifer depth increases. In the NERB study area, the communities of Gillette, Upton, Newcastle, Pine Haven, Hulett, Sundance, Osage, Kaycee, Moorcroft, and Midwest use the Madison aquifer for some or all of their public-water supply (HKM Engineering, Inc., and others 2002a, b).

Both the Madison and Pahasapa Limestones are composed primarily of massive limestone, dolomitic limestone, and dolomite deposited in marine environments (Andrichuk, 1955; Robinson and others, 1964; Sando, 1976a, b; Thayer, 1983; Peterson, 1978, 1984; Sando and Sandberg, 1987). The Madison Limestone is unconformably overlain by the Amsden Formation or Minnelusa Formation and underlain by the Bighorn Dolomite or Jefferson Formation (fig. 7-2). The Pahasapa Limestone is unconformably overlain by the Minnelusa Formation and conformably underlain by the Englewood Formation (also known as Englewood Limestone; fig. 7-2). Thickness of the stratigraphic sequence consisting of the Madison and Pahasapa Limestones and Englewood Formation in the NERB study area ranges from about 200 to 800 ft (Macke, 1993, fig. 44). Thickness estimates of the Pahasapa Limestone in the Black Hills area vary substantially because of karst topography that developed prior to deposition of overlying formations (DeWitt and others, 1986).

Primary (intercrystalline) porosity and permeability generally are very low in the carbonate rocks composing the Madison and Pahasapa Limestones in the study area, although both characteristics are higher in crystalline dolomites than dense limestones (Thayer, 1983; Peterson, 1978, 1984). Consequently, the Madison aquifer is contained primarily within water-saturated parts of both formations where joints, fractures, bedding planes, and (or) solution openings (past and current karst formation) have increased the porosity and permeability sufficiently to create pathways for groundwater circulation in the low-permeability carbonate rocks that compose much of the unit (Hodson and others, 1973; Rahn and Gries, 1973; Wyoming State Engineer's Office, 1974; Huntoon, 1976, 1993; Head and Merkel, 1977; Woodward-Clyde Consultants, 1980; Feathers and others, 1981; Fitzwater, 1981; Thayer, 1983; MacCary, 1984; Downey, 1984, 1986; Kyllonen and Peter, 1987; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Strobel and others, 1999; Carter and others, 2002, and references therein). Location of the zones in both formations with secondary permeability development, including karst/solution features such as enlarged joints, solution cavities, caverns, sinkholes, and collapse breccias, is highly spatially variable, and thus, the Madison aquifer is highly heterogeneous and anisotropic (Woodward-Clyde Consultants, 1980; Fitzwater, 1981; Huntoon, 1976, 1993; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Long, 2000). Permeability of the Madison/Pahasapa Limestones can be substantially enhanced by fractures in areas of structural deformation such as folds and faults. In addition, fracturing and faulting can provide a pathway for vertical movement of groundwater (hydraulic connection) between the Madison aquifer and other Paleozoic aquifers (Huntoon, 1976, 1985a, 1993; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). In fact, interaquifer connection in some parts of the NERB study area has led some investigators to group the Madison and some other Paleozoic aquifers in the PRSB (or parts of the PRSB) and adjacent areas into an aquifer system (Huntoon, 1976, 1985a, 1993; Woodward-Clyde Consultants, 1980; Feathers and others, 1981; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Whitehead, 1996).

Karstic features are common to the outcrop areas of the Pahasapa Limestone in the Black Hills uplift and the Madison Limestone along the eastern flank of the Bighorn Mountains (Sando, 1974, 1976a; Huntoon, 1976). Dissolution of carbonate rocks in parts of the Pahasapa Limestone in the Black Hills uplift has resulted in extensive past and ongoing development of karst solubility features that contribute substantially to groundwater circulation in the Madison aquifer (Sando, 1974; Huntoon, 1976). Much of the Madison aquifer secondary porosity and permeability in the Black Hills uplift likely was created by karstification (solution activity) in the part of the Pahasapa Limestone exposed to weathering and groundwater circulation during the Late Mississippian and prior to deposition of overlying strata (Sando, 1974; old/inactive karst known as paleokarst). Subsequently, karstification of the Pahasapa Limestone returned as the Black Hills was uplifted during the Laramide orogeny, and the increased porosity and permeability from this renewed process is superimposed on the older Mississippian karst development (Sando, 1974; Greene and Rahn, 1995). Numerous caves/caverns, fractures, and other karst features have been identified in the upper part of the Madison aquifer in the Black Hills uplift of South Dakota and Wyoming (Sando, 1974; Peter, 1985; Kyllonen and Peter, 1987; Greene and Rahn, 1995; Strobel and others, 1999). Locally present cavernous zones can provide most of the water produced from some groundwater wells in the Black Hills uplift in Wyoming (Williams, 1948; Whitcomb and others, 1958; Whitcomb and Gordon, 1964). Greene and Rahn (1995) also noted that principal cavern development (and, consequently, principal direction of maximum transmissivity) in the Madison aquifer in the Black Hills area in South Dakota is oriented along the direction of groundwater flow.

In contrast to the enhanced permeability and active groundwater circulation associated with old and new karstic parts of the Pahasapa Limestone in the Black Hills uplift, Huntoon (1976) observed that the extensive paleokarst present in the upper one third of the Madison Limestone along the eastern flank of the Bighorn Mountains was "virtually inactive in terms of groundwater circulation because the karst is now laterally discontinuous due to complete clogging with impermeable shales, silt, and cement, and breccias." Similarly, paleokarst in the Madison Limestone in the Laramie Mountains immediately south of the study area also contributes little to aquifer permeability/circulation for the same reasons (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Huntoon (1976) reported springs from all stratigraphic levels of the Madison Limestone along the eastern flank of the Bighorn Mountains. The investigator noted that most springs issuing from the Madison Limestone south of a fault near Mayoworth, Wyoming discharged from solution-enlarged joints and bedding planes located in the bottom third of the unit.

Small primary porosity and permeability, combined with highly variable amounts of localized secondary porosity and permeability development, is reflected by highly variable Madison aquifer physical characteristics (plate 3). These physical characteristics vary spatially, so availability of groundwater from the Madison aquifer differs substantially from location to location in the NERB study area (for example, Woodward-Clyde Consultants, 1980). Yields for wells completed in the Madison aquifer (an indirect qualitative measure of aquifer permeability/productivity) vary substantially in the NERB study area, but the median well yield for the Madison aquifer (238 gal/min) was larger than all other aquifers except for the Arikaree aquifer in the study area (plate 3). Large well yields ranging from hundreds to more than 1,000 gal/min have been reported for the aquifer in different parts of the NERB study area and adjacent areas, most commonly in and near Madison and Pahasapa Limestone outcrop areas along uplifts surrounding the PRSB, such as the Black Hills uplift (Dana, 1961, 1962; Wyoming State Engineer's Office, 1974; Miller, 1976; Woodward-Clyde Consultants, 1980; Feathers and others, 1981; Kyllonen and Peter, 1987; Strobel and others, 1999) and the eastern flank of the Bighorn Mountains (Wyoming State Engineer's Office, 1974; Huntoon, 1976, 1993; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). Large well yields have been reported in other parts of the NERB study area away from uplifted areas, including areas where the Madison and Pahasapa Limestones are deeply buried in the PRSB and serve as petroleum reservoirs (Hodson, 1974; Feathers and others, 1981; Buelow and others, 1986). However, well yields generally decrease as distance from these uplift/outcrop areas and depth of Madison aquifer burial increases and permeability generally decreases basinward (Huntoon, 1976, 1993). Many of the groundwater wells with large yields are completed in or near geologic structures where deformation has substantially increased Madison aquifer permeability through fracturing and (or) fracture enlargement by solutional activity (Huntoon, 1976, 1993).

Madison aquifer transmissivity in the Black Hills uplift is substantially affected by the volume of fractures and solution openings in a given area. Study of the Madison aquifer near Rapid City, South Dakota, indicated the volume of solution openings was largest near outcrop areas (Greene, 1993). Potential enlargement of fractures by solutional activity (dissolution) is greatest near outcrop areas. Outcrop areas generally correspond to active recharge areas for the Madison aquifer. In outcrop areas, carbon dioxide concentrations in infiltrating recharge waters with low mineralization (dissolved-solids concentrations) substantially increase as the water moves through the soil zone, creating carbonic acid that can cause dissolution of carbonate rock. As the groundwater continues to move into and through the subsurface, more carbonate rock is dissolved and the groundwater becomes more mineralized/saturated as it flows, decreasing the potential for further dissolution, and thus, secondary porosity development. Most of the outcrop of the Pahasapa Limestone is located in South Dakota, so much of the recharge to the Madison aquifer in the Black Hills uplift occurs in South Dakota (Carter and others, 2001a). Except near outcrop areas, groundwater in the Madison aquifer generally is under confined conditions. Artesian pressure in the Madison aquifer is sufficient to cause many of the wells completed in the Madison aquifer to flow at land surface, some at very high flow rates (plate 3). Crist and Lowry (1972) noted that large well yields also were possible from deeply buried parts of Paleozoic lithostratigraphic units with low primary permeability because of high artesian pressures.

Groundwater circulation, including recharge, groundwater flow, and discharge

Recharge to the Madison aquifer within the NERB study area has been interpreted to occur primarily from streamflow losses and infiltration of precipitation on outcrop areas in uplift areas (Rahn and Gries, 1973; Wyoming State Engineer's Office, 1974; Old West Regional Commission, 1976; Boner and others, 1976; Huntoon, 1976; Konikow, 1976; Cooley, 1978; Kyllonen and Peter, 1987; Peterson, 1991; Glass and Sultz, 1992; Hortness and Driscoll, 1998; Carter and others, 2001a, b; Driscoll and Carter, 2001). In the Black Hills uplift area, karst features of the Pahasapa Limestone (where present) provide a conduit for the Madison aquifer to accept recharge from streamflow losses. Recharge to the Madison aquifer in the Black Hills uplift area through exposed outcrops is much greater east of the Wyoming border because most of the Pahasapa Limestone outcrop is located in South Dakota (Carter and others, 2001a, b). In the Black Hills uplift area, precipitation recharge to Madison aquifer outcrops increases with altitude as precipitation increases correspondingly (Carter and others, 2001a, b). Many studies concluded Madison Limestone outcrops along the uplifted mountain flanks and lower foothills surrounding the PRSB likely were the primary source(s) of recharge to the Madison aquifer in the adjacent PRSB (for example, Wyoming State Engineer's Office, 1974; Swenson and others, 1976; Huntoon, 1976; Miller and Strausz, 1980). Potentiometric-surface maps constructed for these and other studies show or suggest groundwater flowing unimpeded from the Madison aquifer outcrop areas in the uplifted mountain flanks and lower foothills along the eastern flanks of the Bighorn Mountains, northern and northeastern flanks of the Laramie Mountains, northern flank of the Hartville uplift (and presumed source of recharge), and the Black Hills uplift through the transition zone between the basin margin and interior, and ultimately into the PRSB interior. Subsequent geologic studies have shown that this interpretation is incorrect for three of these tectonic uplifts (Bighorn and Laramie Mountains and Hartville uplift), because large-displacement range-bounding reverse or thrust faults (or series of faults and folds) formed by compression associated with the Laramide orogeny are located along much of the length of these uplifts surrounding/bordering the PRSB. Where present, these faults (and associated series of faults and folds, where present) sever the lateral continuity of the Madison Limestone/aquifer and other Paleozoic lithostratigraphic/hydrogeologic units and commonly attenuate in overlying Mesozoic units (Blackstone, 1981, 1982, 1988, 1990; Huntoon and Richter, 1981; Western Water Consultants, Inc., 1982b, 1983; Huntoon, 1985a, 1993; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Stone, 2002). Displacements along the faults typically places the Madison aquifer and other Paleozoic lithostratigraphic units in the footwall into contact with impermeable Precambrian crystalline rocks (or Paleozoic strata older than the Madison Limestone) across the fault plane in the hanging wall. Consequently, these faults prevent hydraulic connection from the circulation system(s) in Madison aquifer outcrop areas and immediately downgradient buried areas in the mountainous flanks and lower elevation foothills along the mountain-basin margin (areas in the hanging wall) to the circulation system in the footwall and main body of the aquifer in the PRSB interior. In areas where faulting has juxtaposed the Madison aquifer against other Paleozoic strata instead of Precambrian crystalline rocks, hydraulic connection is unlikely because permeability across the fault is very small because of fault gouge formed during and after Laramide compression (Garland, 1996; Huntoon, 1993). Thus, the "Madison aquifer," including outcrop areas above the PRSB margin along the eastern flank of the Bighorn Mountains, northern and northeastern flanks of the Laramie Mountains, and flanks of the Hartville uplift, is not the same "Madison aquifer" as in the adjacent PRSB interior because faults fully sever unit continuity. Furthermore, the Madison aquifer in the mountainous flanks and lower elevation foothills above the major range-bounding, aquifer-severing faults (and associated faults and folds also created by Laramide compression) commonly is compartmentalized into smaller segments which may have unique groundwater circulation systems with differing recharge, groundwater flow, and discharge characteristics [for example, see descriptions in Stacy (1994) and Garland (1996) of the northern and northeastern flanks of the Laramie Mountains bordering the southern PRSB immediately outside of the NERB study area boundary].

Potentiometric-surface maps have been constructed for all or parts of the Madison aquifer consisting of the Pahasapa and Madison Limestones in the NERB study area and adjacent areas in Wyoming (Swenson, 1974; Wyoming State Engineer's Office, 1974; Swenson and others, 1976; Eisen and others, 1980b; Kyllonen and Peter, 1987; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Bartos and others, 2002), Pahasapa Limestone in South Dakota (Kyllonen and Peter, 1987; Strobel and others, 2000b), or for the Pahasapa and Madison Limestones and all equivalent stratigraphic units composing the aquifer throughout the northern Great Plains in Wyoming, South Dakota, and Montana (Miller and Strausz, 1980; Downey and Dinwiddie, 1988; Whitehead, 1996). Hydraulic-head data used to construct the various maps are most abundant near the uplifted areas, especially the Black Hills uplift, and are sparse to nonexistent in most of the PRSB interior. The basinwide or larger regional maps (Swenson, 1974; Wyoming State Engineer's Office, 1974; Swenson and others, 1976; Eisen and others, 1980b; Miller and Strausz, 1980; Downey and Dinwiddie, 1988; Whitehead, 1996) are highly generalized in most areas because of sparse data, water levels from many different years, and use of many different sources of potentiometric data, including groundwater-level measurements, shut-in pressures, and drill-stem tests; consequently, caution should be exercised when using these maps to examine local conditions, especially in areas with known geologic structures such as faults and folds (anticlines and synclines) (Huntoon, 1985a, b, 1993).

Most of the regional potentiometric-surface maps show groundwater in the Madison aquifer in the NERB study area flowing away from the major uplifts (and presumed sources of recharge) bordering the PRSB into the basin interior, including the Black Hills uplift in the east, Bighorn Mountains in the west, and the Laramie Mountains and Hartville uplift in the south. None of the studies that created the regional potentiometric-surface maps that included all or parts of the NERB study area cited herein specifically examined the effects of geologic structures on groundwater flow/circulation in the Madison aquifer, including the effects of the range-bounding faults described previously, although some acknowledged the potential effects of geologic structures on flow in the aquifer. As described previously, basin-margin reverse or thrust faults sever aquifer continuity along much of the lengths of the structures, limiting potential groundwater inflow into the basin from adjacent Madison aquifer outcrop areas and immediately downgradient buried aquifer areas in the mountainous flanks and lower elevation foothills along the basin margin. This understanding of the effects of range-bounding faulting helps explains why many of the potentiometric-surface maps show steep gradients along the flank of the Bighorn Mountains—some of the hydraulic heads used to construct the maps were from locations in disconnected Madison aquifer groundwater circulation systems located on opposite sides of the range-bounding reverse or thrust faults (Huntoon, 1985a, 1993). Many of the potentiometric-surface maps show contours suggestive of groundwater flowing unimpeded from the Wind River structural basin through the Casper arch and into the Madison aquifer in the southwestern PRSB and PRSB interior (for example, Wyoming State Engineer's Office, 1974; Swenson and others, 1976; Miller and Strausz, 1980). This interpretation of Madison aquifer hydraulic connection between the two structural basins is unlikely because a large thrust fault along the western boundary of the Casper arch (known as the Casper arch thrust fault) separates the basins from one another and severs lateral continuity of Paleozoic strata, including the Madison Limestone/aquifer (for example, Keefer, 1970; Stone, 2002, and references therein).

Unlike the bordering Bighorn and Laramie Mountains and Hartville uplift, a homocline separates the east flank of the PRSB from the Black Hills uplift. Homoclinal basin margins are characterized by stratigraphic and, potentially, hydraulic continuity between the uplifted area and the basin interior. This potentially allows for some Madison aquifer recharge in the Black Hills uplift area to ultimately flow into the PRSB basin interior. Therefore, potentiometric-surface maps constructed exclusively for the Black Hills uplift area or that include the area along with the rest of the NERB study area likely reflect realistic interpretations of the potential for groundwater flowing from the uplifted recharge areas downdip/downgradient and ultimately into the PRSB interior. Many of the other maps seem improbable in showing groundwater flowing into the PRSB from other uplifted areas that likely are disconnected from the aquifer in the basin interior. Consequently, several potentiometric surface maps constructed for the Madison aquifer only in the Black Hills uplift area are presented herein (figs. 7-18 and 7-19). The apparent direction of groundwater flow in the Madison aquifer on these maps is assumed to be perpendicular to the potentiometric-surface contours; however, this assumption is not always valid for highly heterogeneous and anisotropic karstic aquifers. For example, Long (2000) showed how anisotropy in the Madison aquifer in the Black Hills near Rapid City, South Dakota, resulted in groundwater flow nearly parallel to mapped contours in some areas.

In general, potentiometric-surface contours in figs. 7-18 and 7-19 constructed for the Madison aquifer in the Black Hills uplift area show groundwater flowing radially outward from the Black Hills uplift, generally downdip from the limited outcrop area of the aquifer in Wyoming and the much larger outcrop area in South Dakota (DeWitt and others, 1989; Kyllonen and Peter, 1987; Strobel and others, 2000b; Bartos and others, 2002), then flowing and wrapping around the north/northeast and south/southeast Black Hills, and then flowing east without entering deeply into the PRSB interior (see flow arrows on figs. 7-18 and 7-19). This "deflection" of groundwater flow to the east and restriction of the amount of flow into the PRSB has been speculated to be caused by geologic structures (Fanny Peak and Black Hills monoclines and numerous associated folds and faults) separating the Black Hills uplift from the eastern PRSB (Woodward-Clyde Consultants, 1980; Fitzwater, 1981; Downey, 1984). The Madison/Pahasapa Limestone is folded and faulted to varying degrees along the length of both monoclines (Lisenbee and DeWitt, 1993), potentially altering aquifer hydraulic characteristics and horizontal and vertical groundwater flow between the uplifted area and transition to the PRSB interior, especially in areas with substantial fracturing. For example, the largest extensional fractures created by structural deformation along the monoclines likely are located along the crests of the monoclines and oriented parallel to the strike of the structures (direction of maximum transmissivity); consequently, the Madison aquifer could transmit large quantities of water parallel to the strike of the monoclines, and transmit smaller quantities of water or act as a barrier to flow perpendicular to the strike [Fitzwater (1981); also see Huntoon (1985a, b, 1993) for discussion of structural and non-structural disruption/alteration of aquifer hydraulic continuity between uplifted areas and structural basin interiors]. This interpretation of a hydrogeologic effect from the monoclines and an apparent eastern "deflection" of flow may be supported indirectly by geochemical evidence (Eisen and others, 1980b; Woodward-Clyde Consultants, 1980; Fitzwater, 1981; Downey, 1984; Busby and others, 1991; Naus and others, 2001) and recent potentiometric-surface maps constructed for the aquifer in Wyoming and (or) South Dakota (Bartos and others, 2002; Strobel and others, 2000b). In addition, the apparent direction of groundwater flow shown on potentiometric-surface maps for the Madison aquifer portrays groundwater flowing perpendicular to the potentiometric-surface contours; however, this assumption is not always valid for highly heterogeneous and anisotropic karstic aquifers. A much more detailed examination of groundwater levels and other hydrogeologic characteristics from groundwater wells located close to and on both sides of the monoclines is needed to fully understand Madison aquifer continuity and groundwater flow in the vicinity of both structures.

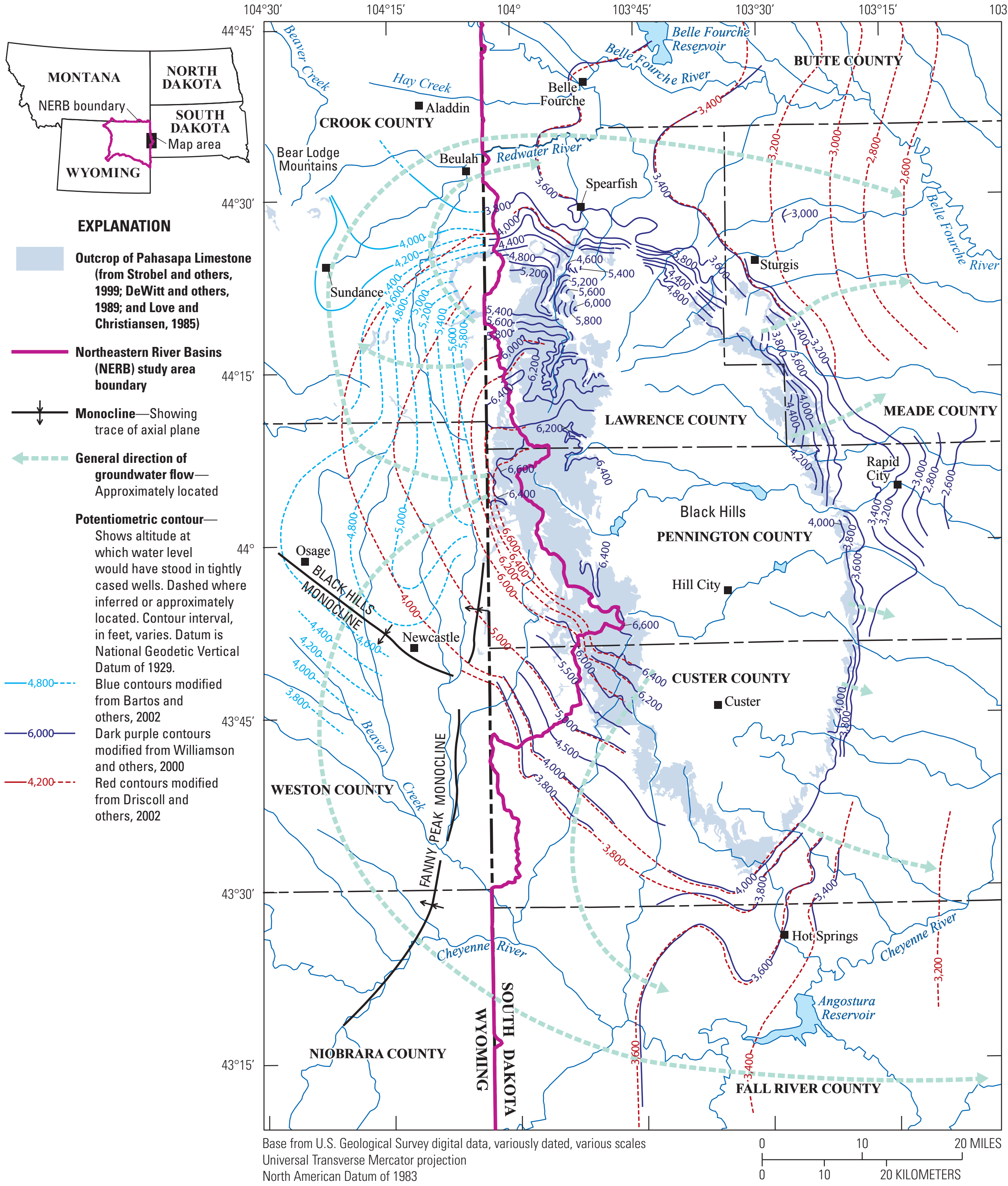
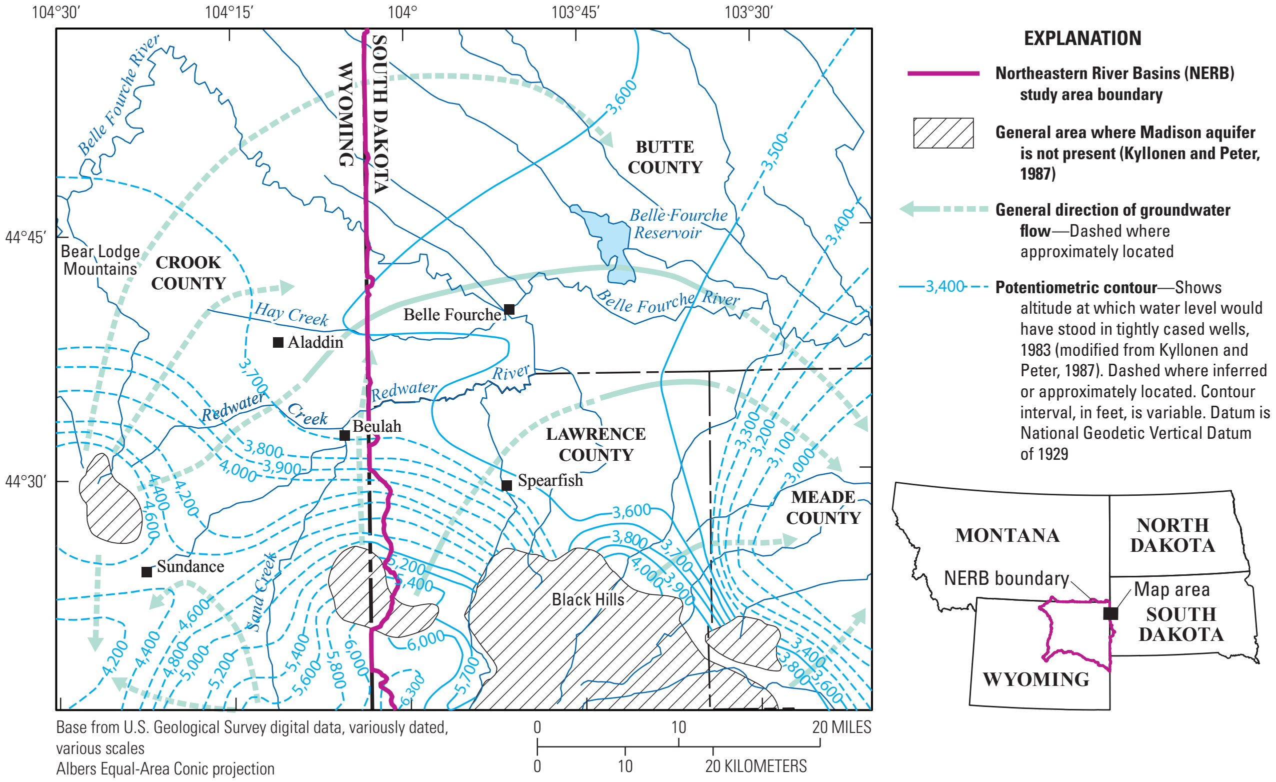


Figure 7-18. Potentiometric surfaces of the Madison aquifer in the Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota.



Base from U.S. Geological Survey digital data, variously dated, various scales
Albers Equal-Area Conic projection
Standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W.
North American Datum of 1983

Figure 7-19. Potentiometric surface of the Madison aquifer in the northwestern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1983.

Discharge from the Madison aquifer occurs naturally through streams, springflows, interaquifer leakage/flow, and anthropogenically through pumpage of groundwater from wells (Swenson, 1968a, b; Rahn and Gries, 1974; Wyoming State Engineer's Office, 1974; Old West Regional Commission, 1976; Boner and others, 1976; Eisen and others, 1980b; Hortness and Driscoll, 1998; Carter and others, 2001a, b). Interaquifer leakage/flow from the Madison aquifer in the Black Hills uplift area likely is very small relative to other hydrologic budget components (Carter and others, 2001a, b). Springs discharging from the Madison aquifer provide flow for many streams in the NERB study area (Swenson, 1968a, b; Wyoming State Engineer's Office, 1974; Old West Regional Commission, 1976; Boner and others, 1976; Huntoon, 1976; Hortness and Driscoll, 1998; Carter and others, 2001a, b). In some areas, springs discharge near the contact of the Minnelusa Formation and Pahasapa Limestone.

Groundwater budget for Black Hills Uplift area

Water budgets have been constructed for the combined Minnelusa and Madison aquifers in the Black Hills uplift area (Carter and others, 2001a; Driscoll and Carter, 2001). Combined water budgets were created because the investigators determined that most of the budget components could not be quantified individually for the two aquifers in the Black Hills uplift area. Detailed average water budgets for the combined Madison and Minnelusa aquifers were created for water years 1950–98 for only South Dakota and for a larger area consisting of South Dakota and part of Wyoming (water budgets reproduced herein as table 7-2; water budget study area extent shown on fig. 7-20. An average water budget for the Wyoming part of the study area was calculated for this study by computing the difference between the water budgets created for these two areas (table 7-2). Inflow budget components consist of recharge from infiltration of streamflow and precipitation on Minnelusa Formation and Madison Limestone outcrops that are connected to the Minnelusa and Madison aquifers, respectively (identified as "connected outcrops" on fig. 7-20). Estimated average annual recharge to the connected outcrop areas of the Minnelusa Formation and Madison Limestone from precipitation is shown on fig. 7-20. Outflow budget components consist of headwater and artesian springflows, well withdrawals, and groundwater outflow. Assuming no change in storage, the sum of the inflow budget components is equal to the sum of the outflow budget components. Recharge from precipitation for the larger study area (consisting of the aquifers in Wyoming and South Dakota) accounted for about 73 percent of recharge (271 of 369 ft³/sec of total inflows), and recharge from streamflow accounted for the remaining 27 percent of recharge (98 of 369 ft³/sec of total inflows). Artesian springflow was the single largest outflow component and accounted for about 46 percent of total outflows (169 of 369 ft³/sec) for the larger study area. Headwater springflow accounted for about 20 percent of the total outflows (72 of 369 ft³/sec) for the larger study area. Consequently, about two-thirds of the total outflow from the Madison and Minnelusa aquifers is from springflows; these springflows then provide flow to Black Hills uplift area streams. Groundwater flowing out of the larger study area accounted for about 27 percent of total outflows (100 of 369 ft³/sec). Well withdrawals accounted for about 8 percent of the total outflows for the larger study area (28 of 369 ft³/sec). All well withdrawals were assumed by the investigators to be in South Dakota because the area considered for Wyoming was located primarily in and near the recharge area where withdrawals were considered to be minor.

Average headwater spring flow for the larger area consisting of Wyoming and Montana (72 ft³/sec; fig. 7-20) is slightly smaller than for the study area consisting of only South Dakota (78 ft³/sec) because measured average flows of about 6 ft³/sec for Beaver and Cold Springs Creek were excluded in the study. The investigators noted that although both streams originate as headwater springs in South Dakota, both streams are depleted by streamflow losses that provide recharge to the Minnelusa aquifer just downstream (west) of the Wyoming border.

Chemical characteristics

The chemical characteristics of groundwater from the Madison aquifer in NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality of the Madison aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (appendices E–3 and G–3).

Environmental water samples

The chemical composition of Madison aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as 66 wells and 3 springs. Summary statistics calculated for available constituents are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram F). TDS concentrations indicated that most waters were fresh (57 of 69 samples, concentrations less than or equal to 999 mg/L)

Table 7-2. Average water budgets for the combined Minnelusa and Madison aquifers in the Black Hills uplift area for water years 1950–98, Wyoming and South Dakota.

[Modified from Driscoll and Carter (2001). ft³/s, cubic foot per second; NC, not calculated; --, not applicable]

Water budget component	Black Hills uplift area in Wyoming and South Dakota		Black Hills uplift area in South Dakota[1]		Black Hills uplift area in Wyoming[2]	
	ft³/s	Acre-feet	ft³/s	Acre-feet	ft³/s	Acre-feet
Streamflow recharge	98	71,000	92	66,600	6	4,400
Precipitation recharge	271	196,300	200	144,900	71	51,400
Headwater springflow	72	52,200	[3]78	56,500	[3]NC	[3]NC
Net recharge[4]	297	215,100	214	155,000	83	60,100
Well withdrawals	[5]28	20,300	[5]28	20,300	[5]--	[5]--
Artesian springflow	169	122,400	128	92,800	41	29,600
Groundwater flow out of study area (outflow)	100	72,400	58	41,900	42	30,500

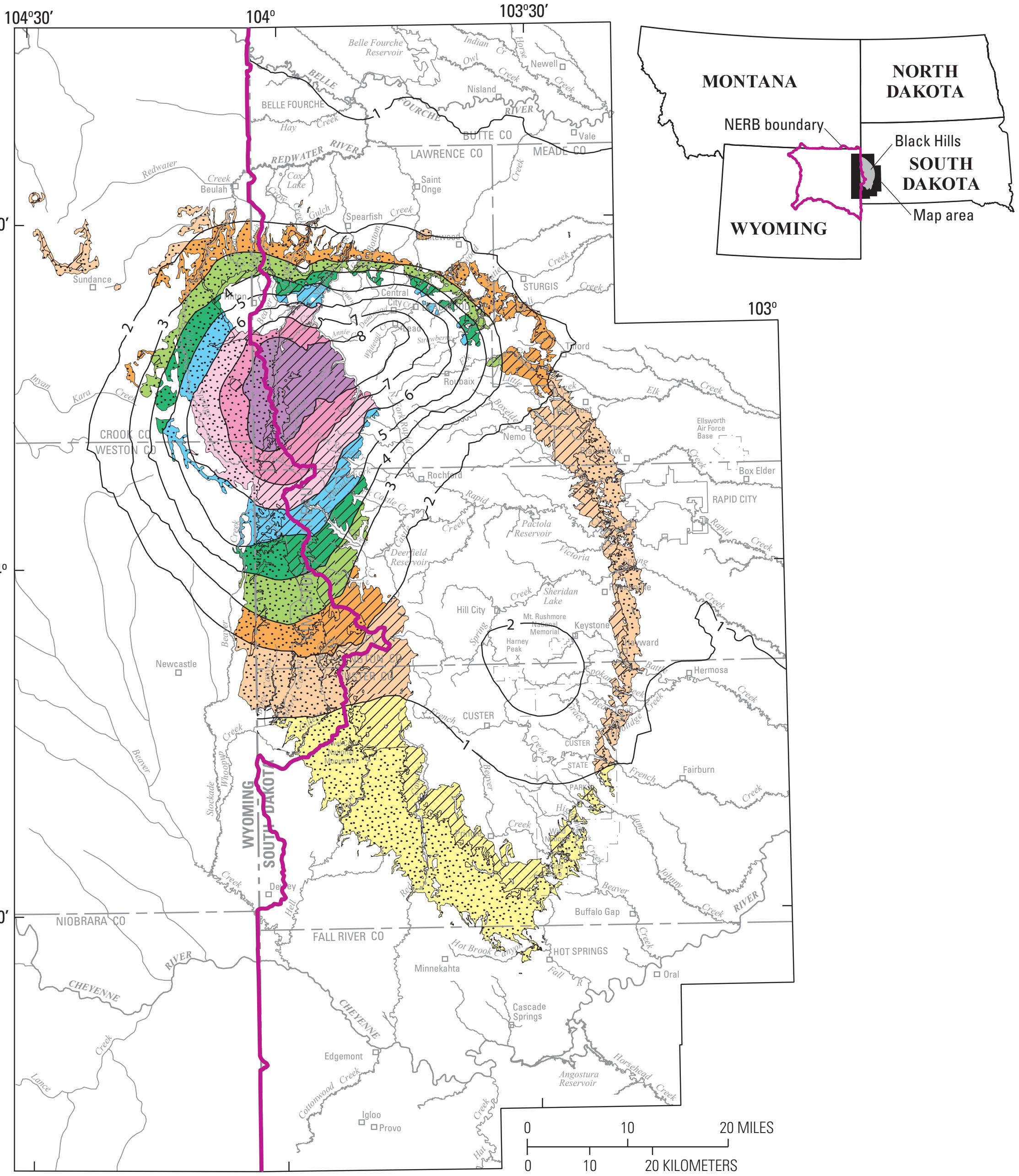
[1] Aquifer outcrop areas for water budgets shown on figure 7–20.

[2] Original study (Driscoll and Carter, 2001) only presented water budgets for Black Hills uplift area in (1) Wyoming and South Dakota, and (2) South Dakota only. Values shown for Wyoming were calculated for this study by computing the difference between the water budgets created for these two areas (four previous columns).

[3] Includes 6 cubic feet per second of discharge for Beaver Creek and Cold Springs Creek in South Dakota, which subsequently recharges Minnelusa aquifer a short distance downstream in Wyoming. Thus, this flow is treated as a discharge for South Dakota; however, discharge and recharge are offsetting when both South Dakota and Wyoming are considered.

[4] Net recharge = (streamflow recharge + precipitation recharge) – headwater springflow.

[5] Identical estimate used for well withdrawals in both areas. Areas considered for Wyoming primarily are recharge areas, where withdrawals are minor.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

EXPLANATION

⁙ **Connected outcrop of Minnelusa Formation for which precipitation recharge is prescribed (modified from Strobel and others, 1999; DeWitt and others, 1989)**

▨ **Connected outcrop of Pahasapa (Madison) Limestone for which precipitation recharge is prescribed (modified from Strobel and others, 1999; DeWitt and others, 1989)**

— **Northeastern River Basins (NERB) study area boundary**

—2— **Line of equal yield potential**—Number indicates average annual yield potential. Interval 1 inch

Average annual recharge, in inches

🟨 Less than 1
🟧 1 to 2
🟧 2 to 3
🟩 3 to 4
🟩 4 to 5
🟦 5 to 6
🟪 6 to 7
🟪 7 to 8
🟪 8 to 9

Figure 7-20. Estimated average annual recharge and average annual yield potential for the Minnelusa Formation and Pahasapa (Madison) Limestone in the Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota (modified from Carter and others, 2001a). Yield potential represents the average depth (in inches) of annual yield, which may occur as streamflow or recharge.

to slightly saline (10 of 69 samples, concentration ranging from 1,000 to 2,999 mg/L), and the remaining waters were moderately saline (2 of 69 samples, concentration ranging from 3,000 to 9,999 mg/L) (appendix E–3; appendix I–3, diagram F). TDS concentrations ranged from 65.0 to 3,490 mg/L, with a median of 454 mg/L.

Concentrations of some characteristics and constituents in water from Madison aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Characteristics and constituents measured at concentrations greater than health-based standards include: strontium (5 of 27 samples exceeded the USEPA HAL of 4,000 μg/L), radium-226 plus radium-228 (2 of 14 samples exceeded the USEPA MCL of 5 pCi/L), lead (23 of 26 samples analyzed for lead listed in appendix E–3 could be compared to the regulatory standard, whereas the remaining 3 samples were censored at a concentration greater than the regulatory standard; of these 23 samples, one exceeded the USEPA action level of 15 μg/L), molybdenum (1 of 29 samples exceeded the USEPA HAL of 40 μg/L), fluoride (2 of 65 samples exceeded the USEPA MCL of 4 mg/L), and arsenic (1 of 37 samples exceeded the USEPA MCL of 10 μg/L). Characteristics and constituents measured at concentrations greater than aesthetic standards (USEPA SMCLs) for domestic use include: TDS (29 of 69 samples exceeded the SMCL of 500 mg/L), sulfate (21 of 69 samples exceeded SMCL of 250 mg/L), iron (11 of 38 samples exceeded the SMCL of 300 μg/L), manganese (11 of 40 samples exceeded the SMCL of 50 μg/L), fluoride (16 of 65 samples exceeded the SMCL of 2 mg/L), chloride (11 of 67 samples exceeded SMCL limit of 250 mg/L), and pH (1 of 65 samples below lower SMCL limit of 6.5 and one sample at upper SMCL limit of 8.5).

Several characteristics and constituents were measured in environmental water samples from the Madison aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured in environmental water samples at concentrations greater than agricultural-use standards include: sulfate (27 of 69 samples exceeded the WDEQ Class II standard of 200 mg/L), chloride (12 of 67 samples exceeded WDEQ Class II standard of 100 mg/L), TDS (11 of 69 samples exceeded WDEQ Class II standard of 2,000 mg/L), radium-226 plus radium-228 (2 of 14 samples exceeded the WDEQ Class II standard of 5 pCi/L), manganese (5 of 40 samples exceeded WDEQ Class II standard of 200 μg/L), iron (2 of 38 samples exceeded the WDEQ Class II standard of 5,000 μg/L), boron (1 of 56 samples exceeded WDEQ Class II standard of 750 μg/L), and SAR (1 of 69 samples exceeded WDEQ Class II standard of 8). Characteristics and constituents measured at concentrations greater than or outside the range of livestock-use standards include: radium-226 plus radium-228 (2 of 14 samples exceeded the WDEQ Class III standard of 5 pCi/L), chromium (1 of 16 samples exceeded WDEQ Class III standard of 50 μg/L), and pH (1 of 65 samples below lower WDEQ Class III limit of 6.5).

Produced-water samples

The chemical composition of groundwater from the Madison aquifer in the NERB study area also was characterized and the quality evaluated on the basis of 54 produced-water samples from wells. Summary statistics calculated for available constituents are listed in appendix G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram E). TDS concentrations from produced-water samples were variable and indicated that most waters were slightly saline (34 of 53 samples, concentration ranging from 1,000 to 2,999 mg/L) to moderately saline (13 of 53 samples, concentration ranging from 3,000 to 9,999 mg/L), and remaining waters were fresh (5 of 53 samples, concentrations less than or equal to 999 mg/L) or briny (1 of 53 samples, concentrations greater than or equal to 35,000 mg/L) (appendix G–3; appendix K–3, diagram E). TDS concentrations ranged from 282 to 53,900 mg/L, with a median of 2,550 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: iron (all 8 samples exceeded the SMCL of 300 μg/L), TDS (50 of 53 samples exceeded SMCL limit of 500 mg/L), sulfate (48 of 54 samples exceeded SMCL of 250 mg/L), chloride (37 of 54 samples exceeded SMCL limit of 250 mg/L), fluoride (1 of 2 samples exceeded SMCL of 2 mg/L), and pH (3 of 48 samples below lower SMCL limit of 6.5 and 2 of 48 samples above upper SMCL limit of 8.5).

Several characteristics and constituents were measured in produced-water samples from the Madison aquifer at concentrations greater than State of Wyoming standards for agricultural and livestock use. Characteristics and constituents measured at concentrations greater than agricultural-use standards include: sulfate (48 of 54 samples exceeded WDEQ Class II standard of 200 mg/L), chloride (40 of 54 samples exceeded WDEQ

Class II standard of 100 mg/L), TDS (39 of 53 samples exceeded WDEQ Class II standard of 2,000 mg/L), SAR (20 of 54 samples exceeded WDEQ Class II standard of 8), iron (2 of 8 samples exceeded WDEQ Class II standard of 5,000 μg/L), and pH (1 of 48 samples below lower WDEQ Class II limit of 4.5 and 2 of 48 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (8 of 53 samples exceeded WDEQ Class III standard of 5,000 mg/L), chloride (6 of 54 samples exceeded WDEQ Class III standard of 2,000 mg/L), pH (3 of 48 samples below lower WDEQ Class III limit of 6.5 and 2 of 48 samples above upper WDEQ Class III limit of 8.5), and sulfate (3 of 54 samples exceeded WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 1 of 53 produced-water samples.

7.4.7 Englewood Formation

Stratigraphically equivalent to part of the lower Madison Limestone, the Englewood Formation (also known as Englewood Limestone) is composed of as much as 50 ft of thin-bedded, locally shaley limestone (Mapel and Pillmore, 1963; Macke, 1993). Hodson and others (1973, sheet 3) speculated that the Englewood Formation "would probably yield little or no water." The Englewood Formation was inferred by Feathers and others (1981) to be a minor aquifer in an aquifer system (Madison aquifer system) consisting of all Paleozoic lithostratigraphic units below the Opeche Shale (confining unit). No data describing the hydrogeologic characteristics of the unit were provided to justify classification as an aquifer. Downey (1984) considered the Englewood Formation to be one of several lithostratigraphic units that collectively function as a regional confining unit to underlying aquifers of Cambrian and Ordovician age in the Northern Great Plains aquifer system. Some studies conducted in the Black Hills uplift in South Dakota include the Englewood Formation as part of the Madison aquifer, apparently as a matter of convenience because the unit commonly is mapped together with the Madison Limestone in the Black Hills area (Strobel and others, 1999; Carter and others, 2002, and references therein). Other studies conducted in the Black Hills in both Wyoming and South Dakota (Kyllonen and Peter, 1987) and in South Dakota (Greene, 1993) consider the Englewood Formation to be a confining unit underlying the Madison aquifer. No information was located describing the physical and chemical hydrogeologic characteristics of the Englewood Formation in the NERB study area.

7.4.8 Jefferson Formation

The Late Devonian-age Jefferson Formation (Jefferson Dolomite in some studies) is present along the eastern flank of the Bighorn Mountains and northwestern PRSB in the NERB study area (Sandberg, 1961, 1967). Langenheim and others (1976) mapped the rocks composing this unit west of Sheridan as the Darby Formation. The Jefferson Formation unconformably underlies the Madison Limestone and unconformably overlies the Bighorn Dolomite throughout most of the formation extent in the study area (Sandberg, 1965, 1967); however, the formation may locally unconformably overlie the Beartooth Butte Formation along the eastern flank of the Bighorn Mountains, a formation of such limited geographic extent that it typically is not shown on geologic maps. The Jefferson Formation commonly is combined with other lithostratigraphic units such as the Madison Limestone on geologic maps that cover the study area. Lithology of the Jefferson Formation along the eastern flank of the Bighorn Mountains was described at four locations in the study area by Sandberg (1967). Lithology at the four study locations consisted primarily of thin-bedded, silty or argillaceous dolomite interbedded with thin beds of dolomite, and measured thickness ranged from 62 to 137 ft. Huntoon (1976) reported a thickness of about 125 ft at the Wyoming-Montana state line and thinning southward to absence between Buffalo and Mayoworth in central Johnson County.

Little hydrogeologic information is available describing the Jefferson Formation, and no data were inventoried describing the physical and chemical hydrogeologic characteristics of the unit in the NERB study area in Wyoming. Huntoon (1976, p. 283) noted that the lack of springs associated with the Jefferson Formation along the eastern flank of the Bighorn Mountains "indicates that it has sufficient permeability to allow water to pass readily to adjacent rocks." Because of this inferred hydrogeologic characteristic, the investigator included the unit as part of the Madison aquifer along the eastern flank of the Bighorn Mountains, defined by the investigator as consisting of the Tensleep and Amsden Formations, Madison Limestone, Jefferson Formation, and Bighorn Dolomite (Huntoon, 1976, p. 285).

The potential use of Paleozoic lithostratigraphic units along the eastern flank of the Bighorn Mountains as source(s) of water supply for the city of Sheridan was evaluated through an exploratory well drilling and testing project (Western Water Consultants, Inc., 1982a; Howard, Needles, Tammen, and Bergendoff, 1985). The feasibility study for this project considered the Jefferson Formation a potential aquifer within an aquifer system identified as the Madison aquifer, defined as consisting of three lithostratigraphic units: the uppermost being the Madison Limestone, middle was the Jefferson Formation, and lowermost was the Bighorn Dolomite (Western Water Consultants, Inc., 1982a, plate 1). The Jefferson Formation (identified as "unnamed Devonian rocks") was one of several lithostratigraphic units penetrated during drilling of two wells to evaluate hydrogeologic characteristics of Paleozoic lithostratigraphic units located west of Sheridan along the eastern flank of the Bighorn Mountains (Howard, Needles, Tammen, and Bergendoff, 1985). Both wells penetrated the full thickness of the Jefferson Formation during drilling (about 108 ft), and the formation was described as consisting primarily of dolomite with interbedded sandstone, shale, and limestone. The investigators concluded the Jefferson Formation was not a potential source of water supply (aquifer), because at both drilling locations measured water production did not increase and water chemistry did not change as the formation was penetrated during drilling. In addition, the investigators noted that data obtained during drilling were insufficient to evaluate whether the formation prevented vertical water movement between the overlying Madison Limestone and underlying Bighorn Dolomite.

7.4.9 Beartooth Butte Formation

The Early Devonian-age Beartooth Butte Formation is a lithostratigraphic unit of very limited geographic extent in the NERB study area. Present only in small areas along the eastern flank of the Bighorn Mountains, the Beartooth Butte Formation unconformably overlies the Bighorn Dolomite and unconformably underlies the Jefferson Formation (fig. 7-2; Sandberg, 1961, 1967). Sandberg (1967, p. 54) described the formation at the study location along Little Bighorn Canyon as a silty, sandy, argillaceous dolomite conglomerate with pebbles, cobbles, and boulders consisting of Bighorn Dolomite; measured formation thickness was 8 ft. At a study location in South Fork Rock Creek, Sandberg (1967, p. 81) described the formation as a limestone conglomerate with pebbles consisting of Bighorn Dolomite, interbedded with grayish-red shale in the lower 4 ft; measured formation thickness was 22 ft. No data were inventoried describing the physical and chemical hydrogeologic characteristics of the Beartooth Butte Formation in the NERB study area in Wyoming.

7.4.10 Bighorn and Whitewood aquifers

The physical and chemical characteristics of the Bighorn and Whitewood aquifers in the NERB study area are described in this section of the report.

Physical characteristics

Present in the northwestern and west-central western PRSB and adjacent eastern flanks of the Bighorn Mountains and the northeastern PRSB and adjacent Black Hills uplift area, the Ordovician-age Bighorn Dolomite and stratigraphically equivalent Whitewood Dolomite consists primarily of thin-bedded to massive dolomite, with locally occurring dolomitic limestone (Hose, 1955; Mapel, 1959; Richards and Nieschmidt, 1961; Macke, 1993). A fine- to coarse-grained sandstone known as the Lander Sandstone Member commonly comprises the basal part of the Bighorn Dolomite (Kirk, 1930; Miller, 1930; Mapel, 1959; Macke, 1993, figs. 2, 19). The Whitewood Dolomite in the eastern PRSB and Black Hills uplift areas also is known as the Red River Formation in some studies and regionally outside of Wyoming. Throughout most of the study area, the Bighorn Dolomite is unconformably overlain by either the Madison Limestone or Jefferson Formation, and is unconformably underlain by the Gallatin Limestone or Gros Ventre Formation where the Gallatin Limestone is not present (fig. 7-2). Locally, in the eastern flank of the Bighorn Mountains, the Bighorn Dolomite can be unconformably overlain by the Beartooth Butte Formation and underlain by the Harding Sandstone equivalent (fig. 7-2). The Whitewood Dolomite is conformably underlain by the Winnipeg Formation (fig. 7-2). Thickness of the Bighorn and Whitewood Dolomites decreases southward from more than 400 ft in the northern PRSB to an "erosional zero-edge along an east-west and northeast-southwest line extending from the northern Black Hills to the southern Bighorn Mountains" (Macke, 1993, p. M53).

Previous studies classified the Bighorn and Whitewood Dolomites in the NERB study area as potential aquifers or as aquifers in areas where local geologic and hydrogeologic conditions are favorable (Lowry and Cummings, 1966; Whitcomb and others, 1966; Hodson and others, 1973; Huntoon, 1976; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983; MacCary and others, 1983), and those definitions are retained herein (fig. 7-2). Kyllonen and Peter (1987) considered the Whitewood Dolomite and the overlying Englewood Formation and underlying Winnipeg Formation to be part of a sequence of "confining beds" separating the Madison aquifer from the Deadwood aquifer in the Black Hills uplift area in South Dakota and Wyoming. Strobel and others (1999) considered the Whitewood Dolomite to be a semi-confining unit separating the Madison and Deadwood aquifers in the Black Hills uplift area in South Dakota. Huntoon (1976) included the Bighorn Dolomite as part of an aquifer system (Madison aquifer) located along the eastern flank of the Bighorn Mountains, defined by the investigator as consisting of the Tensleep and Amsden Formations, Madison Limestone, Jefferson Formation, and Bighorn Dolomite in hydraulic interconnection (1976, p. 285). Similarly, Feathers and others (1981, fig. II-4) considered the Bighorn and Whitewood Dolomites to be parts of a regional Paleozoic aquifer system (Madison aquifer system) present throughout most of the NERB study area consisting of all Paleozoic strata below the Goose Egg Formation and equivalent units and above Precambrian igneous and metamorphic rocks. The Bighorn and Whitewood Dolomites were classified as major aquifers in the Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9). In regional (multistate) studies, the USGS grouped the Bighorn Dolomite and Whitewood Dolomites with other Cambrian-age and Middle- and Late-Ordovician-age lithostratigraphic units into an areally extensive regional hydrogeologic unit identified as the "Cambrian-Ordovician aquifer/aquifer system" of the Northern Great Plains aquifer system (Downey, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995) or alternatively as one of several units composing the "lower Paleozoic aquifers" of the Northern Great Plains aquifer system (Whitehead, 1996).

Despite being classified as potential aquifers or as aquifers, relatively little information is available describing the hydrogeologic characteristics of the Bighorn and Whitewood Dolomites in the NERB study area. Excluding a few wells associated with petroleum exploration and development, data describing the physical and chemical characteristics from wells completed exclusively in the Bighorn and Whitewood aquifers were not inventoried as part of this study, despite the aquifer being known to yield water to occasional groundwater wells located in or near outcrop areas (plate 3; Feathers and others, 1981, table IV-4). It is possible that some groundwater wells believed to be exclusively completed in the Madison aquifer also may be completed in the underlying Bighorn aquifer. For example, two groundwater wells open to both the Bighorn aquifer and the overlying Madison aquifer were inventoried in the Kaycee area (Western Water Consultants, Inc., 1983, table 1).

Because of predominantly carbonate composition, investigators indicate that potential development of the Bighorn and Whitewood aquifers as sources of water supply likely are greatest in and near outcrop areas where secondary porosity and permeability in the form of joints, fractures, bedding-plane partings, and solution openings/caverns have developed (Lowry and Cummings, 1966; Whitcomb and others, 1966; Hodson and others, 1973; Huntoon, 1976; Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). For example, Hodson and others (1973, sheet 3) speculated that yields ranging from "20 to several hundred gal/min should be available from solution cavities and fractures in the Bighorn Dolomite in and near outcrop areas." Huntoon (1976) observed that most springs issuing from the Bighorn Dolomite along the eastern flank of the Bighorn Mountains discharged water from both joints and bedding planes, indicating that these two features provided most of the formation permeability. Furthermore, he noted few caves in the Bighorn Dolomite, indicating that large-scale karstification of the formation has yet to begin along the eastern flank of the Bighorn Mountains and is unlikely to provide much permeability.

The Bighorn Dolomite was penetrated during drilling of two exploratory wells constructed to evaluate hydrogeologic characteristics of Paleozoic lithostratigraphic units located west of Sheridan along the eastern flank of the Bighorn Mountains (Howard, Needles, Tammen, and Bergendoff, 1985). Both wells penetrated the full thickness of the Bighorn Dolomite during drilling (about 363 ft), and the formation was described as consisting primarily of dolomite with thin interbeds of shale, dolomitic limestone, and limestone. Water production measured during penetration of the formation indicated a relatively low-yielding aquifer at both drilling locations, with flows of 10 and 17 gal/min measured after air circulation was stopped. Most water flow was from the lower part of the Bighorn Dolomite, and the investigators concluded the upper part of the formation was relatively impermeable and may behave as a confining unit.

Using geologic and hydrogeologic data, MacCary and others (1983) identified potentially favorable areas where the Whitewood Dolomite (identified as the Red River Formation) in Wyoming and adjacent states might yield more than 500 gal/min to wells completed in the unit. Three criteria were used in the evaluation to identify these areas (MacCary and others, 1983, p. E4), including "(1) the presence of rocks with porosity, as indicated by electric-log analyses, equal to or greater than 10 percent and with a thickness greater than 100 ft; (2) the presence of dolomite with an average grain size greater than 0.0625 mm [millimeters] and with a thickness greater than 100 ft; and (3) the presence of geologic structures that could cause greater secondary permeability, and, therefore, larger well yields." Using these criteria, "favorable areas" identified in Wyoming were small in geographic extent and limited primarily to the northern Black Hills uplift area.

Chemical characteristics

The chemical characteristics of groundwater from the Bighorn and Whitewood aquifers in NERB study area are described using environmental and produced-water samples in this section of the report. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (table 5-1), and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values.

7.4.11 Bighorn aquifer

The chemical composition of groundwater from the Bighorn aquifer in the NERB study area 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 G–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix K–3, diagram F). TDS concentrations from produced-water samples were variable and indicated that most waters were moderately saline (4 of 5 samples, concentration ranging from 3,000 to 9,999 mg/L), and the remaining water was slightly saline (1 of 5 samples, concentration ranging from 1,000 to 2,999 mg/L) (appendix G–3; appendix K–3, diagram F). TDS concentrations ranged from 1,304 to 9,061 mg/L, with a median of 5,286 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured at concentrations greater than aesthetic standards for domestic use include: TDS (all 5 samples exceeded SMCL limit of 500 mg/L), sulfate (all 5 samples exceeded SMCL of 250 mg/L), and pH (1 of 5 samples above upper SMCL limit of 8.5). Characteristics and constituents measured in produced-water samples at concentrations greater than agricultural-use standards include: sulfate (all 5 samples exceeded WDEQ Class II standard of 200 mg/L), TDS (4 of 5 samples exceeded WDEQ Class II standard of 2,000 mg/L), chloride (4 of 5 samples exceeded WDEQ Class II standard of 100 mg/L), SAR (2 of 5 samples exceeded WDEQ Class II standard of 8), and pH (1 of 5 samples above upper WDEQ Class II standard of 9). Characteristics and constituents measured at concentrations greater than livestock-use standards include: TDS (3 of 5 samples exceeded WDEQ Class III standard of 5,000 mg/L), sulfate (3 of 5 samples exceeded WDEQ Class III standard of 3,000 mg/L), and pH (1 of 5 samples above upper WDEQ Class III limit of 8.5).

7.4.12 Whitewood aquifer

The chemical composition of groundwater from the Whitewood aquifer in the WRSB was characterized and the quality was evaluated on the basis of one environmental water sample. Individual constituent concentrations are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram G). The TDS concentration from the well (465 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 1,000 mg/L). Two constituents (iron and manganese) were measured at concentrations greater than the USEPA aesthetic standards for domestic use (SMCLs of 300 and 50 μg/L, respectively). No characteristics or constituents exceeded applicable State of Wyoming agricultural or livestock water-quality standards.

7.4.13 Winnipeg confining unit and "Harding Sandstone equivalent"

The Ordovician-age Winnipeg Formation is present in parts of the northeastern PRSB and adjacent Black Hills uplift. Many studies only recognize two members, the Roughlock Member (also known as Roughlock Siltstone Member) and the Icebox Member (McCoy, 1952; Foster, 1972). Macke (1993) recognized three members—from stratigraphically youngest to oldest, the uppermost Roughlock Member consisting primarily of siltstone, with some fine-grained sandstone, limestone and silty shale; the middle Icebox Shale Member (or Icebox Member) consisting primarily of shale; and the lowermost Black Island Member (known as Aladdin Sandstone or Winnipeg Sandstone in older/other studies) consisting primarily of fine- to medium-grained sandstone (McCoy, 1952; Foster, 1972; Blankennagel and others, 1977; Macke, 1993). Where present, the Winnipeg Formation unconformably underlies the Bighorn Dolomite.

Rocks stratigraphically equivalent to the Winnipeg Formation are located in the adjacent western and northwestern PRSB and eastern flank of the Bighorn Mountains. These strata consist primarily of sandstone and are informally named the "Harding Sandstone equivalent" for an equivalent sequence of rocks present in central Colorado (fig. 7-2; Love and others, 1993; Macke, 1993, and references therein). Along the northeastern flank of the Bighorn Mountains, the Harding Sandstone equivalent unconformably underlies another lithostratigraphic unit consisting primarily of mineralogically similar fine- to very fine-grained sandstone named the Lander Sandstone Member of the Bighorn Dolomite (Kirk, 1930; Miller, 1930; Mapel, 1959; Macke, 1993, figs. 2, 19). Thickness of the Winnipeg Formation and Harding Sandstone equivalent in the NERB study area increases from less than 20 ft in the south, southwest, and northwest to 140 ft or more in northwestern Crook County (Macke, 1993, fig. 25).

The water-bearing characteristics of the Winnipeg Formation are rarely evaluated in previous studies conducted exclusively in Wyoming because of the fine-grained composition of much of the unit and availability of water from other lithostratigraphic/hydrogeologic units known to produce water. No data were inventoried describing the physical and chemical hydrogeologic characteristics associated with wells completed in either unit in the NERB study area in Wyoming. Hodson (1973) speculated that potential yield from the Winnipeg Formation likely was less than 10 gal/min. Because of the substantial amounts of fine-grained rocks present in the unit, Feathers and others (1981) classified the Winnipeg Formation in the NERB study area as a confining unit in one part of the report (table IV-1); however, the investigators contradicted this definition in a different part of the report (fig. II-4) by showing the formation combined with the Bighorn and Whitewood Dolomites into an aquifer (Ordovician aquifer) within a Paleozoic aquifer system (Madison aquifer system).

Several USGS studies with a regional (multistate) emphasis included the Winnipeg Formation as part of an areally extensive regional hydrogeologic unit identified as the "Cambrian-Ordovician aquifer/aquifer system" of the Northern Great Plains aquifer system (Downey, 1986; Downey and Dinwiddie, 1988; Busby and others, 1995). These studies noted the large sandstone content of the Winnipeg Formation and equivalent strata in other states, but did not note the primarily fine-grained composition of the lithostratigraphic unit throughout much of the study area in Wyoming (Macke, 1993). More detailed USGS hydrogeologic studies conducted in the Black Hills uplift within Wyoming and (or) South Dakota have classified the Winnipeg Formation in the area as a confining unit (Kyllonen and Peter, 1987; Greene, 1993) or semi-confining unit (Strobel and others, 1999; Carter and others, 2002, and references therein).

Parts of the formation composed largely of sandstone may have some water-development potential where burial depth is not too great. In the northeastern PRSB, Blankennagel and others (1977) noted the Black Island Member (identified by the investigators as the Winnipeg Sandstone) consisted of 96 ft of clean, well-sorted, medium-grained sandstone at a USGS test well in Crook County. However, sandstone in the unit in the PRSB commonly contains silica cement and is frequently quartzitic, especially where buried deeply by thousands of feet of overlying strata that likely reduces porosity substantially (Peterson, 1978).

Because geologic studies indicate the Winnipeg Formation in the NERB study area consists largely of rocks with low porosity/permeability and many hydrogeologic studies have classified the formation as a confining unit, the unit tentatively is classified as a confining unit herein (fig. 7-2). No information describing the physical and chemical hydrogeologic characteristics of the Harding Sandstone equivalent was located.

7.4.14 Gallatin and Gros Ventre hydrogeologic units

The physical and chemical characteristics of the Gallatin hydrogeologic unit and the physical characteristics of the Gros Ventre hydrogeologic unit in the NERB study area are described in this section of the report.

Physical characteristics

The Gallatin and Gros Ventre hydrogeologic units consist of water-saturated and permeable parts of two lithostratigraphic units present in the western PRSB and eastern flank of the Bighorn Mountains, respectively named after geologic formations (fig. 7-2), as follows. The Cambrian-age Gallatin Limestone consists of hard limestone and conglomeratic limestone interbedded with shale (Hose, 1955; Mapel, 1959). The Cambrian-age Gros Ventre Formation consists of shale, dense limestone, and some sandstone (Hose, 1955; Mapel, 1959). Combined, maximum thickness of both formations is as much as 600 ft in northern Johnson County (Hose, 1955; Mapel, 1959).

The water-bearing characteristics of both formations in the NERB study area are poorly known, and most characterization of both formations as hydrogeologic units is speculative. Hodson (1973) speculated that potential yield from either formation was limited, and likely was less than 10 gal/min. Because of lithology, most studies consider the formations to be confining units or leaky confining units (Feathers and others, 1981; Western Water Consultants, Inc., 1982a, 1983). The Wyoming Water Framework Plan (WWC Engineering and others, 2007, fig. 4-9) classified both formations in the NERB study area as minor aquifers, most likely because of a study indicating good water-yielding characteristics at an exploratory test well located west of Sheridan along the eastern flank of the Bighorn Mountains (Howard, Needles, Tammen, and Bergendoff, 1985).

Chemical characteristics

The chemical characteristics of groundwater from the Gallatin hydrogeologic unit in the NERB study area are described using produced-water samples in this section of the report. Groundwater quality of the Gallatin hydrogeologic unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards, and groundwater-quality sample summary statistics tabulated by hydrogeologic unit (appendix G–3; table 5-1).

The chemical composition of groundwater from the Gallatin hydrogeologic unit in the NERB study area was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in appendix G–3. TDS concentrations measured in both wells (2,509 and 2,705 mg/L) indicated both waters were slightly saline (concentration ranging from 1,000 to 2,999 mg/L).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Characteristics and constituents measured in both produced-water samples from the Gallatin hydrogeologic unit at concentrations greater than aesthetic standards for domestic use include: TDS (SMCL limit of 500 mg/L), chloride (SMCL limit of 250 mg/L), and sulfate (SMCL of 250 mg/L).

Characteristics and constituents measured in both produced-water samples from the Gallatin hydrogeologic unit at concentrations greater than agricultural-use standards include: SAR (WDEQ Class II standard of 8), TDS (WDEQ Class II standard of 2,000 mg/L), chloride (WDEQ Class II standard of 100 mg/L), and sulfate (WDEQ Class II standard of 200 mg/L). No characteristics or constituents were measured in either water sample at concentrations greater than applicable State of Wyoming livestock water-quality standards.

7.4.15 Flathead and Deadwood aquifers

The physical and chemical characteristics of the Flathead aquifer and the physical characteristics of the Deadwood aquifer in the NERB study area are described in this section of the report.

Physical characteristics

Present in the western PRSB and adjacent eastern flank of the Bighorn Mountains, the Cambrian-age Flathead Sandstone consists of fine-to coarse-grained sandstone as much as 340 ft in thickness in the NERB study area (Hose, 1955; Mapel, 1959). The Cambrian-age Deadwood Formation consists of locally dolomitic or conglomeratic sandstone with interbeds of shale, siltstone, limestone, and dolomite as much as 500 ft in thickness in the NERB study area (Mapel and Pillmore, 1963; Robinson and others, 1964).

The water-bearing characteristics of both formations are poorly understood in the NERB study area, and the formations typically are classified as aquifers because of their hydrogeologic characteristics outside of the study area. Hodson and others (1973) inferred that both formations were aquifers and speculated that potential yields from both the Flathead Sandstone and Deadwood Formation likely were as much as 20 gal/min. Both units were classified as aquifers by Feathers and others (1981), and that definition is tentatively retained herein (fig. 7-2). The Wyoming Water Framework Plan classified the Flathead Sandstone as a major aquifer (WWC Engineering and others, 2007, fig. 4-9). The Deadwood Formation is considered a local aquifer in the Black Hills area of South Dakota (Strobel and others, 1999; Carter and others, 2002). Although both formations are considered aquifers or potential aquifers in all previous studies, they are essentially undeveloped or rarely developed in the NERB study area because of deep burial and (or) availability of water from other aquifers at most locations.

Chemical characteristics

The chemical characteristics of groundwater from the Flathead aquifer in NERB study area are described using environmental water samples in this section of the report. Groundwater quality of the Flathead aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards, and groundwater-quality sample summary statistics tabulated by hydrogeologic unit (appendix E–3; table 5-1).

The chemical composition of groundwater from the Flathead aquifer in the NERB study area was characterized and the quality evaluated on the basis of environmental water samples from as many as two wells. Individual constituent concentrations are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram H). TDS concentrations measured in water from both wells (112 and 793 mg/L) indicate that the water is fresh (TDS concentrations less than or equal to 999 mg/L).

Concentrations of some characteristics and constituents in water from wells completed in the Flathead aquifer in the NERB study area exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Two constituents were measured in one environmental water sample at activities or concentrations greater than USEPA health-based standards: radium-226 plus radium-228 (the one available sample exceeded the USEPA MCL of 5 pCi/L) and fluoride (1 of 2 samples exceeded the USEPA MCL of 4 mg/L). One characteristic (TDS) and two constituents (chloride and fluoride) were measured in one of two environmental water samples at concentrations greater than USEPA aesthetic standards for domestic use (SMCL limits of 500 mg/L, 250 mg/L, and 2 mg/L, respectively).

Concentrations of some characteristics and constituents in water from wells completed in the Flathead aquifer exceeded State of Wyoming standards for agricultural and livestock use in the NERB. Two constituents were measured in environmental water samples at activities or concentrations greater than agricultural-use standards: radium-226 plus radium-228 (the one available sample exceeded the WDEQ Class II standard of 5 pCi/L) and chloride (1 of 2 samples exceeded WDEQ Class II standard of 100 mg/L). One constituent (radium-226 plus radium-228) was measured in one environmental water sample at an activity greater than the livestock-use standard (WDEQ Class III standard of 5 pCi/L).

7.5 PRECAMBRIAN BASAL CONFINING UNIT

The physical and chemical characteristics of the Precambrian basal confining unit in the NERB study area are described in this section of the report.

Physical characteristics

Where underlying all younger lithostratigraphic units, Precambrian igneous and metamorphic rocks serve as a basal confining unit to all overlying hydrogeologic units in the NERB study area (Feathers and others, 1981; Downey and Dinwiddie, 1988). These rocks are found primarily in the core of uplifted areas surrounding the PRSB. Locally permeable zones from joints, fractures, and weathered zones in areas of outcrop generally provide only small quantities of water to wells at most locations (Hodson and others, 1973; Feathers and others, 1981).

Chemical characteristics

The chemical characteristics of groundwater from the Precambrian basal confining unit in the NERB study area are described using environmental water samples in this section of the report. Groundwater quality of the Precambrian basal confining unit is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards, and groundwater-quality sample summary statistics tabulated by hydrogeologic unit (appendix E–3; table 5-1).

The chemical composition of groundwater from the Precambrian basal confining unit in the NERB study area was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in appendix E–3. Major-ion composition in relation to TDS is shown on a trilinear diagram (appendix I–3, diagram I). The TDS concentration from the spring (63.0 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L). On the basis of the characteristics and constituents analyzed, the quality of water from the one spring flowing from the Precambrian basal confining unit in the NERB was suitable for most uses. No characteristics or constituents exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater from the Precambrian basal confining unit in the NERB also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations are listed in appendix G–3. The TDS concentration measured in the produced-water sample (3,718 mg/L) indicated that the water was moderately saline (concentration ranging from 3,000 to 9,999 mg/L).

The available water-quality analyses were from produced-water samples, for which chemical analyses of few characteristics 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. Two characteristics (pH and TDS) and two constituents (chloride and sulfate) exceeded USEPA aesthetic standards for domestic use [SMCLs of 8.5 (upper limit), 500 mg/L, 250 mg/L, and 250 mg/L, respectively]. Three characteristics (pH, SAR, and TDS) and two constituents (chloride and sulfate) exceeded the applicable State of Wyoming standards for agricultural use [WDEQ Class II standards of 9 (above upper limit of 8.5), 8 (unitless), 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively]. One characteristic (pH) was measured at a value greater than the applicable State of Wyoming livestock water-quality standard (above upper WDEQ Class III standard of 8.5).

Chapter 8

Groundwater development and basinwide water balance

Karl G. Taboga and James E. Stafford

This chapter discusses groundwater development, withdrawals, consumptive uses, and depletions in the Powder/Tongue/Northeast River basins (NERB).

The terms "withdrawal" and "consumptive use" are used throughout this chapter. A groundwater withdrawal is simply the removal of a volume of water from a well or a spring at its source. Throughout this study, "use" has essentially the same meaning as "withdrawal." The "consumptive use" of a water resource, however, diminishes the amount of water available for other uses and effectively removes that water as a useable resource from the drainage basin. Consumptive processes include plant and animal growth, evaporation, transpiration by plants, and some industrial processes (Sharp, 2007). Evaporation and transpiration combined (referred to as evapotranspiration) constitute the largest consumptive loss of water resources in most river basins. The U. S. Geological Survey (USGS) defines groundwater depletion as, "long-term water-level declines caused by sustained groundwater pumping" (USGS, 2019). However, this chapter also looks at groundwater "depletion" as the volume of pumped groundwater that is unlikely to return to its source aquifer in any substantial amount.

Relatively few uses are wholly consumptive or non-consumptive. Most uses are partially consumptive; meaning some of the water is lost while the remainder returns to the system. For example, evapotranspiration and plant growth consume a large fraction of the groundwater used for irrigation, but smaller portions return to the basin as flow to surface water and as recharge to groundwater. Other examples of partially consumptive uses (with the associated consumptive constituent noted in parentheses) include livestock watering (animal growth and evaporation), reservoir storage (evapotranspiration), and domestic wastewater treatment such as discharge from sewage or septic systems (evapotranspiration). Other uses, such as industrial wastewater storage and disposal in lined evaporation pits, are wholly consumptive.

In a similar manner, only a minor fraction of water withdrawn from wells is returned to a basin's groundwater system. The amount of water lost from groundwater storage is a depletion. In the example above, the groundwater lost to evapotranspiration and surface outflows represents a depletion; only a small amount of the withdrawn water re-enters the ground surface below irrigated fields and return flow channels as recharge. In the same way, a minor portion of the 922,000 ac-ft of groundwater withdrawn (WOGCC, 2018) in the Powder River Basin during coalbed methane development (2002–2018) was returned to groundwater storage. Much of the produced water was lost to evapotranspiration and outflows into neighboring states when it was discharged into unlined on-channel evaporation/infiltration pits or into streams. Depletions also reduce groundwater discharges to streamflow thereby reducing available surface water resources (Barlow and Leake, 2012). Groundwater depletions are well documented near past and current coalbed methane fields (Taboga and others, 2015; 2017).

Information for this chapter was compiled from multiple sources:

- Previous and current water plans for the Powder/Tongue and Northeast basins (HKM Engineering, 2002a, b; RESPEC, 2019a, b)
- Numerous previous local and regional studies (app. B, chap. 7)
- Groundwater permit data provided by the Wyoming State Engineer's Office (SEO), the Montana Department of Natural Resources and Conservation (MDNRC), the South Dakota Department of Environment and Natural Resources (SDDENR), and the Nebraska Department of Natural Resources (NDNR)
- The SEO 2016 Hydrographers' Annual Reports Water Division 1 and 2 (Wyoming State Engineer's Office, 2016) available at: http://seo.wyo.gov/documents-data/hydrographer-reports
- Produced groundwater data from the Wyoming Oil and Gas Conservation Commission (WOGCC, 2018)

8.1 INFORMATION FROM PREVIOUS WATER PLANS

The Wyoming Statewide Framework Water Plan (WWC Engineering and others, 2007) lists estimated groundwater withdrawals and consumptive uses, compiled from the 2002 Powder/Tongue and Northeast basins plans and the associated technical memoranda (HKM, 2002a, b). There are, however, minor differences in the volumes reported between the plans and the various technical memoranda, which is likely due to the estimation methods used. Additionally, RESPEC Company LLC (RESPEC) provided groundwater withdrawal and consumptive-use data from their recent Powder/Tongue River Basin Level 1 Study (2019a) and Northeast River Basin Level 1 Study (2019b).

8.2 GROUNDWATER WITHDRAWAL AND CONSUMPTIVE-USE ESTIMATIONS IN THIS MEMORANDUM AND BASINWIDE WATER BALANCE

In the absence of direct measurements, groundwater withdrawals and consumptive uses must be estimated. This is more complex than it would appear because multiple estimations of the same parameter may be made using different methods and assumptions. Still, the methods used must provide reasonably conservative estimations of withdrawals and consumptive uses based on rational assumptions. The tables, shown below, present ranges of probable withdrawals and consumptive uses in multiple formats. In some cases, the tables provide conservative estimations for comparison. For example, compare the SEO permitted irrigation and livestock withdrawals in table 8-1a to science-based estimates of actual withdrawals (RESPEC, 2019a, b).

The water resources of any river basin are not composed of static volumes of standing water. Unlike an area's mineral reserves, water is a dynamic resource. It enters a basin as precipitation or as surface water, and groundwater inflows and exits as effluent flow or as evapotranspiration (see definition, chap. 5). It is important to understand the transient nature of water resources. For this reason, the Wyoming State Geological Survey (WSGS) generated a basin-wide water balance (tables 8-2a and 8-2b) to provide a sense of the magnitude, origin, and fate of water resources in the NERB.

8.2.1 Groundwater withdrawal and consumptive-use estimations

Tables 8-1a through 8-1e summarize groundwater withdrawal and consumptive-use estimates from the SEO and previous Wyoming Water Development Commission (WWDC) river basin plans (HKM Engineering, 2002a, b; WWC Engineering and others, 2007; RESPEC, 2019a, b) for principal SEO listed water right withdrawals. Consumptive-use estimates from the median economic growth and normal water-demand year scenario are shown for each withdrawal (Agricultural, Municipal/Rural Domestic Water Systems, Industrial, and Miscellaneous). These use sectors combine principal SEO-listed water right uses:

- Agricultural uses (irrigation and stock watering (table 8-1a)
- Municipal and rural domestic supplies are combined (table 8-1b)
- Industrial uses (table 8–1c)
- Other diverse uses (table 8–1d) that involve miscellaneous, monitoring, testing, and multi-use wells hereinafter referred to as minor uses

Additionally, consumptive-use estimates are provided from the 2019 Powder/Tongue and Northeast Basin plans (RESPEC, 2019a, b) for comparison to the values prorated from the technical memoranda of the 2002 Powder/Tongue and Northeast Basin plans (HKM, 2002a, b). The values developed for tables 8-1a through 8-1e and tables 8-2a through 8-2d are typically shown to a precision of three significant figures. Percentages are typically carried to one decimal place in the tables; in some cases, small percentages are carried to two decimal places (table 8-2c).

Estimates of total withdrawal and consumptive-use volumes for the six use sectors listed above are shown in tables 8-1a through 8-1d and are aggregated in table 8-1e. Irrigation and stock watering withdrawals are combined as agricultural uses in table 8-1a, and public supply and rural domestic withdrawals are combined in table 8-1b. Total average annual groundwater withdrawal during 2002–2018 is estimated at 189,000 ac-ft, and the highest estimated value for annual consumptive use is 150,000 ac-ft (table 8-1e). Water-use categories, amounts, and estimation methods are discussed in more detail later in this chapter. Minor uses are not included in the totals shown in table 8-1e because only SEO-permitted withdrawal data (table 8-1d) are available, and minor uses were not addressed in previous water plans.

For other uses, potential volumes calculated from SEO allocated well yields are provided for comparison to consumptive-use estimates obtained from previous water basin plans or from data compiled and processed by the WSGS. The large differences between SEO allocated well yields and actual use estimates show that the volumes of groundwater used constitute, in most cases, a minor fraction of what has been allocated to permitted water right holders. For example, the total irrigation withdrawal calculated from SEO-permitted yields for "likely existing wells" (157,000 ac-feet/yr in table 8-1a) assumes continuous year-round operation of the permitted irrigation wells. Although the value is clearly an overestimate, it does provide a useful upper limit of groundwater withdrawals for irrigation readily compared to estimates of actual consumptive uses, in this case 12,600 ac-feet/yr in table 8-1a. Estimates shown for agricultural withdrawals and consumptive uses of groundwater are aggregate values for both irrigation and stock watering provided in previous reports (RESPEC, 2019a, b). Irrigation consumptive uses in those reports are based on actual crop-specific consumptive uses specified in Pochop and others (1992) applied to crop-distribution data obtained from the agricultural industry in the target basins. The methods used are explained in appendices of the 2002 and 2019 Powder/Tongue and Northeast basin plans (HKM, 2002a, b; RESPEC, 2019a, b).

Table 8-1a. Groundwater withdrawal and consumptive use estimates for agricultural use wells (irrigation and stock watering) in the Wyoming portion of the NERB.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive use (ac-ft/yr)	Percent consumptive use	Estimation method/data sources/notes
SEO permitted irrigation wells [a]	252,000	no estimate	no estimate	SEO permitted yields for irrigation wells through 10/7/15 (See table 8-6)
	157,000	no estimate	no estimate	SEO permitted yields for likely existing irrigation wells through 10/7/2015 (See table 8-6)
SEO permitted livestock wells [a]	176,000	no estimate	no estimate	Total permitted yield through 10/7/2015 (See table 8-6)
	135,000	no estimate	no estimate	Permitted yield for likely existing stock wells through 10/7/2015 (See table 8-6)
Agricultural uses [b, c]	7,940 livestock	7,940	100.0%	Irrigation and livestock use estimates are aggregated as agricultural uses. Mean annual crop consumptive use of groundwater for 1971–1998 in NERB is 80% of withdrawals Stock use considered 100% consumptive
	15,800 irrigation	12,600	79.7%	

[a] Wyoming State Engineer's Office, 2017

[b] RESPEC, 2019a, b

[c] C. McCutcheon, written commun., 2017

Table 8-1b. Groundwater withdrawal and consumptive use estimates for municipal and domestic use wells in the Wyoming portion of the NERB.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive use (ac-ft/yr)	Percent consumptive use	Estimation method/notes
Permitted municipal and domestic wells [a]	185,000	no estimate	no estimate	Total permitted yield through 10/7/2015 (table 8-6)
	129,000	no estimate	no estimate	Permitted yield for likely existing wells through 10/7/2015 (table 8-6)
Municipal/community groundwater use [b]	9,590	5,260	55%	Consumptive municipal water use calculated by subtracting 4,323 ac-ft of wastewater returns from annual withdrawals
Rural domestic use [b]	3,350	3,350	100%	Rural domestic use assumed to be 100% consumptive
Total	**12,940**	**8,610**	66.5%	Combined municipal and rural domestic use

[a] Wyoming State Engineer's Office, 2018

[b] RESPEC, 2019a, b

Table 8-1c. Groundwater withdrawal and consumptive use estimates for industrial use wells in the Wyoming portion of the NERB.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive use (ac-ft/yr)	Estimation method/notes
Permitted non-CBNG industrial wells [a]	108,000	no estimate	Total permitted yield through 10/7/2015 (See table 8-6)
	31,800	no estimate	Total permitted yield for likely existing wells through 10/7/2015 (See table 8-6)
Electrical energy generation, refineries, other industry [b]	5,100	5,100	Electrical power plants, Newcastle refinery, misc. industry
Coalbed natural gas produced water [c]	61,500	61,500	CBNG production only Assumed to be 100% consumptive
Oil and gas produced water [c]	52,500	52,500	Includes no CBNG production Assumed to be 100% consumptive
Disposal well volumes [c]	-------	-3,500	Returned to groundwater storage
Injection well volumes [c]	-------	-28,200	Returned to groundwater storage
Estimated water use for coal mines [d]	33,100	33,100	Water volumes based on short tons of coal produced in the PRB multiplied by use coefficients Assumed to be 100% consumptive
Total	**152,200**	**120,500**	

[a] Wyoming State Engineer's Office, 2018

[b] HKM, 2002a, b; RESPEC, 2019a, b

[c] Wyoming Oil and Gas Conservation Commission, 2018

[d] Lovelace, 2009; USEIA, 2018

Table 8-1d. Permitted annual groundwater withdrawal rates for SEO monitor, multi-use, and other wells in the Wyoming portion of the NERB.

SEO permitted use	Annual withdrawal [a] (ac-ft/yr)	Annual consumptive use (ac-ft/yr)	Estimation method/notes (See table 8-6)
Permitted monitor wells	957	no estimate	Total permitted yield through 10/7/2015
	255	no estimate	Permitted yield for likely existing wells through 10/7/2015
Permitted "other wells"	662,000	no estimate	Total permitted yield through 10/7/2015
	123,000	no estimate	Permitted yield for likely existing wells through 10/7/2015
Permitted "multi-use wells"	1,620,000	no estimate	Total permitted yield through 10/7/2015
	921,000	no estimate	Permitted yield for likely existing wells through 10/7/2015

[a] Wyoming State Engineer's Office (2018)

Table 8-1e. Total groundwater withdrawal and consumptive use estimates for all uses in the NERB.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive use (ac-ft/yr)	Percent consumptive use	Estimation method/notes
Total permitted yield Wyoming	2,120,000	no estimate	no estimate	Permitted yield for likely existing wells through 10/7/2015 (See table 8-6)
	1,950,000	no estimate	no estimate	Permitted yield for non-CBM likely existing wells through 10/7/2015 (See table 8-6)
Total permitted and likely drilled yield Wyoming, Montana, South Dakota, and Nebraska [a,b,c,d]	2,120,000	no estimate	no estimate	1,362 WSEO permits as of 10/7/2015 262 MDNRC permits as of 04/03/15 77 SDDENR permits as of 03/09/15 1 NDNR permit as of 11/03/15 (See tables 8-6, 8-7, 8-8)
Estimated withdrawals and consumptive uses from Wyoming agricultural, municipal, domestic and industrial wells	189,000	150,000	79.4%	Totals of estimates from Tables 8-1a, 8-1b, and 8-1c

[a] Wyoming State Engineer's Office (2018)

[b] Montana Department of Natural Resources and Conservation (MDNRC, 2017)

[c] South Dakota Department of Environment and Natural Resources (SDDENR, 2017)

[d] Nebraska Department of Natural Resources (NDNR, 2017)

8.3 BASIN-WIDE WATER BALANCE

Tables 8-2a and 8-2b contain mass balance water budget calculations for the Wyoming portion of the NERB. The water balance analysis provides an estimate of basin-wide evapotranspiration. In the process, streamflow, consumptive-use, and recharge data from this and other chapters in this report are compiled into one table (table 8-2a). Armed with these estimates, first-order approximations can be made of the proportions of precipitation destined for recharge, evapotranspiration, surface water outflows, and consumptive uses from water resource development.

The analysis contained in table 8-2a is adapted from the general water budget equation (Fetter, 2001):

Evapotranspiration = (precipitation + surface inflow + imported water + groundwater inflow) – (surface water outflow + groundwater outflow + reservoir evaporation + exported water + recharge) ± changes in surface water storage ± changes in groundwater storage

The assumptions used in this water balance are:

- Water is neither imported into nor exported from the NERB
- Basin groundwater inflows plus outflows equal zero
- The water budget mass balance model examines annual fluxes of water resources in the NERB. The assumption that long-term changes in groundwater storage equal zero, used in previous groundwater memoranda (Taucher and others, 2013; Taboga and others, 2014a, b), cannot be applied because large volumes of groundwater are coproduced with oil, gas, and coal annually in the NERB (see chap. 10 of this report). A complete listing of groundwater depletions is shown in table 8-2c.

8.3.1 Precipitation

Precipitation is the ultimate source of groundwater recharge. Average annual precipitation volume in the NERB for the 30-year period of record (POR) from 1981 to 2010 was calculated using GIS software and PRISM data (http://prism.oregonstate.edu/, fig. 3-3) at 18,800,000 ac-ft.

Table 8-2a. NERB water resources mass balance.

Water balance parameters [a]		Average annual volume (ac-ft)
Precipitation (1981–2010 - figure 3-3) [b]		18,800,000
Total surface water inflows [c]	+	3,100
Total surface water outflows [c]	-	891,000
Groundwater discharged to the surface from municipal/domestic, livestock, and industrial uses[d]	+	137,000
Evaporation from reservoirs: [e]	-	47,700
Total estimated NERB recharge [f]	-	433,000
Basinwide evapotranspiration	=	**17,568,000**
Comparative estimates (ac-ft)		
Estimated evapotranspiration in the NERB from the USGS climate and land-cover data regression [g]		*17,089,000*
Estimated evapotranspiration in the NERB from the WSGS climate and land-cover data regression [h]		*17,449,000*

[a] Fetter , C.W., 2001

[b] PRISM Climate Group, 2012

[c] USGS, 2018

[d] Tables 8-1a, 8-1b, 8-1c

[e] RESPEC, 2019a, b

[f] Table 6-3

[g] Sanford and Selnick, 2013

[h] Taboga and Stafford, 2016

Table 8-2b. Water balance parameter volumes as percent of precipitation in the Wyoming portion of the NERB.

Water balance parameters[a]	Percent of precipitation [b]
Net stream outflows[c]	4.7%
Evaporation from reservoirs[d]	0.2%
Surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses[d]	0.3%
Total estimated NERB recharge (table 6-3)	2.3%
Basinwide evapotranspiration	93.4%
Total	**100.9%**

[a] Fetter , C.W., 2001

[b] PRISM Climate Group, 2012

[c] USGS, 2018

[d] RESPEC, 2019a, b

8.3.2 Surface water inflows and outflows

Average annual stream inflow and outflow data for the Wyoming portion of the basin were obtained from the USGS (http://water.usgs.gov/). USGS streamflow gaging station 06429500 at Buckhorn, Wyoming, monitors inflows from Cold Spring Creek entering Wyoming from South Dakota. Annual outflow data were recovered from USGS stream gaging stations sited on effluent reaches of the Little Bighorn, Tongue, Powder, Little Powder, Little Missouri, Belle Fourche, Upper Niobrara, and Cheyenne rivers, and Redwater Creek.

8.3.3 Groundwater discharged to surface

Annual water production volumes for traditional oil and gas (TOG), coalbed methane (CBM), and injection/disposal wells were obtained from operator-supplied data as reported to the WOGCC (2018). Groundwater production volumes associated with coal mining were calculated by multiplying annual coal production (U.S. Energy Information Administration, 2018) by groundwater production rates per short ton of coal mined (Lovelace, 2009). The volume of produced groundwater discharged to the surface was calculated as mean annual groundwater produced from oil, gas, and coal development minus mean annual produced water volumes pumped into injection and disposal wells.

Groundwater depletions from municipal/domestic and livestock uses were obtained from the 2019 Powder/Tongue and Northeast basins water plans (RESPEC, 2019a, b). Irrigation uses were not considered because 99.9 percent of irrigation water is lost to evapotranspiration and return flows (Colorado State University, 2013), and the USGS (Sanford and Selnick, 2013) and WSGS (Taboga and Stafford, 2016) models calculate cropland-specific evapotranspiration rates.

8.3.4 Evaporation from reservoirs

The 2019 Powder/Tongue and Northeast basins water plans (RESPEC, 2019a, b) provided reservoir evaporation data.

8.3.5 Total estimated NERB recharge

The recharge value shown is the “best total recharge” estimate for sedimentary aquifers calculated in tables 6-2 and 6-3 from the recharge fraction data in Taboga and Stafford (2016) and PRISM (2013) precipitation data for the 1981–2010 POR.

8.3.6 Estimated basin-wide evapotranspiration

The water balance model adapted from Fetter (2001) and presented in table 8-2a places basin-wide evapotranspiration at 17,600,000 ac-ft per year. For comparison, estimates of actual evapotranspiration in the NERB are shown at the bottom of table 8-2a. These estimates were obtained using GIS based regression models developed by the USGS (Sanford and Selnick, 2013) and the WSGS (Taboga and Stafford, 2016) from environmental data. The results of the two regression models agree closely with the evapotranspiration calculated in the water balance.

8.4 MAGNITUDE, ORIGIN, AND FATE OF WATER RESOURCES IN THE NERB

Table 8-2b shows that more than 93 percent of precipitation is lost to evapotranspiration in the NERB, about 2 percent recharges the basin's aquifers, and nearly 5 percent leaves as stream outflow. Evaporation from reservoirs constitutes about 0.2 percent of total basin precipitation. Combined surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses comprise 0.3 percent of precipitation. The total percentage exceeds 100 percent of precipitation because groundwater contributions to each parameter are not considered.

Table 8-2c summarizes various average annual (2002-2016) groundwater demand estimates from tables 8-1a through 8-1c as percentages of estimated recharge. Aggregated municipal and domestic consumptive uses constitute about 2 percent of recharge. Estimated total annual demands for all uses (156,700 ac-ft; table 8-1e) constitute about 36 percent of annual average recharge. Average annual industrial demand (120,000 ac-ft) represents almost 28 percent of recharge; however, recent annual industrial demand has decreased substantially (e.g. 76,500 ac-ft in 2016) as energy production declined in the Powder River Basin (WOGCC, 2018). Chapter 10 of this report examines groundwater production by the energy industry in detail.

Estimated recharge (table 8-2c) exceeds average annual withdrawals of groundwater. Estimates of total average annual groundwater use could be substantially higher and the estimates of recharge substantially lower without significantly changing these simple, comparative results.

Table 8-2d evaluates future groundwater requirements relative to recharge. The 2019 Powder/Tongue and Northeast basins water plans (RESPEC, 2019a, b) provide use factor-based projections of total combined annual withdrawals and consumptive uses for agricultural, municipal/rural domestic, recreational, and industrial uses in 2045. The analyses examines normal and maximum water demand for low-, moderate-, and high-economic-growth scenarios. Projected future annual groundwater requirements for the 25-year timeframe are determined as percentages of annual recharge estimated in chapter 6. These estimates apparently do not consider demands from the oil, gas, and coal industries, and, any estimates for the energy sector are likely to be speculative, given the rapidly changing global energy market.

Overall, groundwater consumptive uses projected for 2045 range from 9.7 percent of recharge for the low-growth scenario to 12.9 percent for the high-growth scenario. Estimated recharge volumes are likely adequate to meet not only current withdrawals (table 8-2c) but future groundwater demands as well. The potential for overutilization is location specific, both hydrologically and legally, and must be evaluated during the planning stage of any development project. Evaluating potential groundwater resources of the NERB outside of existing environmental regulations and legal restrictions is beyond the scope of this study.

Table 8-2c. Summary of groundwater use statistics as percentage of recharge in the Wyoming portion of the NERB.

Groundwater-use statistics	Annual volume (ac-ft)	Percentage of calculated recharge
Estimated recharge (ac-ft) to sedimentary aquifers[a]	433,000	-----
Average annual groundwater consumptive uses		
Agricutural uses (irrigation and stock watering)[b]	23,700	5.5%
Municipal and domestic[b]	13,000	3.0%
Industrial[b]	120,000	27.7%
Total	**156,700**	**36.2%**

[a] Table 6-3

[b] Tables 8-1a-d

Table 8-2d. Summary of future groundwater requirements as percentages of recharge.

Economic scenario	Low growth	Mid growth	High growth
Groundwater demand 2045 consumptive use (ac-ft)[a]	41,987	44,628	55,992
Percentage of estimated recharge	9.7%	10.3%	12.9%

[a] RESPEC, 2019a, b

The following sections discuss the uses that account for nearly all estimated groundwater withdrawals in the 2019 Powder/Tongue and Northeast basins water plans (RESPEC, 2019a, b) and the 2007 Statewide Framework Water Plan (WWC Engineering and others, 2007). Tables 8-6 through 8-8 show the number of groundwater permits by use for the portions of Wyoming, Montana, South Dakota, and Nebraska, respectively. The "other" category includes miscellaneous wells.

8.4.1 Agricultural uses (irrigation, livestock watering, and dairy)

Irrigation and livestock uses are aggregated as agricultural uses in this report. Previous basin water plans do not present direct measurements of groundwater volumes used for irrigation. Instead, the previous plans estimate use based on actual crop-specific consumptive uses delimited/defined in Pochop and others (1992) and applied to crop-distribution data obtained from the agricultural industry in the Powder/Tongue and Northeast basins. HKM (2002a, b — Tab D in both reports) estimated actual surface water and groundwater depletions (consumptive uses) for irrigation during wet, normal, and dry conditions.

In the NERB, most irrigation wells are in the High Plains aquifer system of the Niobrara River Basin and along the alluvium of the Tongue River (fig. 8-1). Irrigation uses are largely consumptive due to the proportion of water lost to evapotranspiration. RESPEC provided the irrigation use estimates shown in table 8-1a (RESPEC, 2019a, b). Within the NERB, the SEO has issued 319 permits solely for irrigation use. Total agricultural use permits and permitted yields are shown in tables 8-6 through 8-9. The USGS shows localized groundwater level declines of less than 50 ft in the High Plains Aquifer around Lusk and in northeastern Goshen County (McGuire, 2017).

Livestock wells are widely distributed throughout the NERB (fig. 8-2). Withdrawals and consumptive uses for livestock watering (table 8-1b) were calculated using seasonally adjusted daily water requirements for beef cattle, dairy cows, horses, sheep, goats, and pigs (C. McCutcheon, written commun., 2017). It was assumed that all livestock water use is consumptive. In the NERB, the number of permits issued solely for stock watering (tables 8-6 through 8-9) are 10,714 in Wyoming, 32 in Montana, 8 in South Dakota, and 1 in Nebraska (tables 8-6 through 8-9).

8.4.2 Municipal and rural domestic water systems

The 2019 Powder/Tongue and Northeast basins water plans (RESPEC, 2019a, b) provide municipal and rural domestic water systems data (table 8-1b). Municipal groundwater use (9,180 ac-ft/year) calculated by RESPEC shows close agreement with total annual water-use numbers (9,140 ac-ft/year) reported by public water system managers to WWDC and SEO (WWDC, 2016; Water Guy, LLC, 2017).

As of October 7, 2015, the SEO issued 109 permits for exclusive municipal use and 6,539 domestic-use permits in the NERB (table 8-6). Montana (table 8-7) and South Dakota have issued 23 and 46 domestic-use permits, respectively (table 8-8). In addition to the municipal-use permits, some of the wells that supply water to the basin's smaller communities in Wyoming (table 8-12) are permitted as multiple use or miscellaneous wells (fig. 8-7).

8.4.3 Industrial uses

Groundwater is the primary source for industrial uses in the NERB (RESPEC, 2019a, b; Lovelace, 2009; HKM, 2002a, b), due in large part to oil, gas, and coal development. The market forces and extractive technologies that drive the pace of energy resource development (and the industry's requirements for groundwater) vary widely over time. Residents of the NERB are all too familiar with the area's cycle of "boom and bust." Chapter 10 of this report discusses the magnitude and variability of groundwater production associated with energy development during 2002–2018.

Consumptive losses for oil, gas and coal production were assumed to constitute 100 percent of groundwater withdrawals minus the volumes returned to groundwater storage by injection and disposal wells. In fact, an undetermined fraction of groundwater withdrawn during energy development infiltrates into shallow aquifers from unlined produced water storage pits and streambeds where surface discharge is permitted. The volume of produced water used consumptively during energy development has been a controversial issue in the NERB for decades.

Not all industrial uses of groundwater are ultimately extractive. Some groundwater co-produced during oil and gas development is disposed by reinjection into geologic units. Water injection into existing hydrocarbon reservoirs can extend and enhance oil production. Table 10-1 shows the annual volumes of produced water injected into wells sited in the NERB during 2002–2016; injection data was not available for 2017 and 2018 at the time of writing. Further information about enhanced oil recovery is available at the Schlumberger website, http://www.slb.com/services/technical_challenges/enhanced_oil_recovery.aspx.

Permitted yields for SEO industrial permits as well as average annual volumes of produced water and injected water for 2002–2016 are provided in table 8-1c. Figure 8-5 shows the locations of SEO permitted industrial use wells. Although CBM wells are not shown, some industrial wells in figure 8-5 are permitted for use in coalmines or building aggregate mines. Figure 10-1 shows the location of oil and natural gas wells, and coal mines where groundwater is produced in association with energy development.

8.5 INFORMATION FROM HYDROGEOLOGIC UNIT STUDIES

In addition to the withdrawal and consumptive-use data compiled from numerous sources, aquifer-specific groundwater-use information was compiled from a variety of sources for the chapter 7 discussion of hydrogeologic units in the NERB. Chapter 7 summarizes the physical, hydrogeologic, and chemical characteristics of the principal hydrogeologic units in the NERB, including the known dynamics of recharge, discharge, and groundwater circulation.

Appendix B provides a chronological summary of the locations, aquifers, focus, results, and status of groundwater development studies in the NERB sponsored by the WWDC since 1973. Many of these studies were used to compile the information presented in chapter 7.

8.6 GROUNDWATER PERMIT INFORMATION

Groundwater development proceeds primarily by installing water supply wells and, to a lesser degree, by developing natural springs. Permits allowing the appropriation of groundwater are issued and administered by the SEO, the Montana Department of Natural Resources and Conservation (MDNRC), the South Dakota Department of Environment and Natural Resources (SDDENR), and the Nebraska Department of Natural Resources (NDNR). For this study, the WSGS acquired groundwater permit data from all of these agencies. The SEO provided information for more than 66,000 groundwater permits through October 7, 2015 (table 8-6). Groundwater permit data is also listed for Montana (table 8-7), South Dakota (table 8-8), and Nebraska (table 8-9). Additional information about the groundwater permit databases is given in appendix C. Information for specific Wyoming groundwater permits can be accessed through the SEO online water rights database, http://seo.state.wy.us/wrdb/PS_WellLocation.aspx. The database is easy to use, and specific information can be queried using various search parameters (e.g., permit number, location, applicant, use).

Information on specific groundwater permits from the out-of-state agencies can be accessed online:

http://dnrc.mt.gov/divisions/water/water-rights for the MDNRC

https://denr.sd.gov/des/wr/dbwrsearch.aspx for the SDDENR

http://dnr.ne.gov/gwr/groundwaterwelldata for the NDNR

In this study, permits to appropriate groundwater in the NERB are mapped by SEO class-of-use (figs. 8-1 through 8-7). Additional groundwater permit data are tabulated in this chapter to summarize the number of permits by:

1. SEO permit status, depth range, and yield range (tables 8-3 through 8-5)
2. Class–of-use for Wyoming, Montana, South Dakota, and Nebraska (tables 8-6 through 8-9)
3. SEO municipal use, including producing hydrogeologic unit (tables 8-10 through 8-11)
4. Wyoming Department of Environmental Quality (WDEQ) Source Water Assessment Program (SWAP; table 8-12)

8.6.1 Groundwater permits by permit status

Table 8-3 presents the number of groundwater permits issued by the SEO under five permit-status categories. Table 8-3 does not include permits from Montana, South Dakota, or Nebraska. In Wyoming, the status categories are:

1. Fully Adjudicated—the well has been drilled and inspected, and a certificate of appropriation issued
2. Complete—SEO has received a notice of completion of the well
3. Unadjudicated—the well has not yet been inspected but may have been drilled
4. Incomplete—SEO has not received a notice of completion of the well
5. Undefined—a permit without a designated status. These include the following discontinued status categories:
   - Abandoned—SEO has received a notice that the well has been physically abandoned
   - Expired—the permit to appropriate groundwater has expired, generally because SEO has not received a notice that the well has been completed within the time specified in the original permit or extension(s)
   - Cancelled—the permit has been cancelled, generally by the original permit applicant

The SEO issues permits granting water rights to applicants. This does not necessarily mean that a well has been completed, and in most cases, it is not known with certainty whether a well was installed in association with a specific permit. To estimate the number of wells that have likely been completed for each use, the WSGS assumed that wells have been completed for fully adjudicated, complete, abandoned, and unadjudicated permits. In contrast, wells are likely not completed in association with incomplete and undefined permits. Table 8-3 summarizes the number of likely drilled wells for each use in the NERB. Based on these assumptions, at least 72 percent of wells permitted through 2002 are likely to have been installed (i.e., completed) compared to at least 54 percent of wells permitted after 2002.

8.6.2 Groundwater permits by depth and yield

Tables 8-4 and 8-5 show the number of SEO permits by depth range and by yield range, respectively.

Approximately 52 percent of all SEO groundwater permits for which depth data are available (table 8-4) are for wells less than 500 ft deep, and nearly 18 percent are for wells less than 100 ft deep. Almost 75 percent of SEO groundwater permits issued after 2002 were for wells more than 500 ft deep, and approximately 54 percent were for wells more than 1,000 ft deep. The incidence

Table 8-3. SEO groundwater permits in the NERB listed by permit status.

Permit status	All permits	New permits since 2002
Fully adjudicated	782	56
Complete	47,288	14,992
Unadjudicated	111	96
Incomplete	17,801	12,496
Undefined	706	207
Total permits	**66,688**	**27,847**
Probable wells drilled	*48,181–66,688* *(72–100%)*	*15,144–27,847* *(54–100%)*

of recent well depths greater than 500 ft is likely biased by the inclusion of CBM well permits, which constitute 68 percent of all permits issued after 2002 (table 8-6). A substantial fraction of permits (49 percent issued after 2002 and 26 percent overall) does not include well depth (table 8-4).

Of the 57,008 groundwater permits in the NERB database for which yield information is available (table 8-5), approximately 67 percent of all permits and 57 percent of wells permitted since 2002 are allowed yields of 1–25 gallons per minute (gpm). Approximately 6 percent of all permits and 7 percent of permits issued after 2002 allow yields greater than 100 gpm. Less than one-half percent of permits issued both since 2002 and in total are for yields greater than 1,000 gpm. A small portion of permits (8 percent issued after 2002 and 15 percent overall) in the SEO database do not include permitted yield.

Permitted depths and yields, and the mapped permit locations on figures 8-1 through 8-7 illustrate that most wells in the NERB are completed in Tertiary hydrogeologic units.

Table 8-4. SEO groundwater permits in the NERB listed by yield range.

Depth range (ft)	All permits		Cumulative	
	Permits	Percentage	Permits	Percentage
1–50	5,885	11.93%	5,885	11.93%
51–100	2,958	5.99%	8,843	17.92%
101–500	16,971	34.39%	25,814	52.31%
501–1000	11,460	23.22%	37,274	75.53%
> 1000	12,074	24.47%	49,348	100.00%
Total permits with depth information	49,348	--	--	--
Permits with no depth information	17,340	26.00%	66,688	--
Total permits	**66,688**	**(of total)**	--	--

Depth range (ft)	New permits since 2002		Cumulative	
	Permits	Percentage	Permits	Percentage
1–50	679	4.78%	679	4.78%
51–100	280	1.97%	959	6.75%
101–500	2,599	18.30%	3,558	25.06%
501–1000	3,007	21.18%	6,565	46.23%
> 1000	7,635	53.77%	14,200	100.00%
Total permits with depth information	14,200	--	--	--
Permits with no depth information	13,647	49.01%	27,847	--
Total permits	**27,847**	**(of total)**	--	--

Table 8-5. Wyoming SEO groundwater permits in the NERB listed by yield range.

Yield range (gpm)	All permits		Cumulative	
	Permits	Percentage	Permits	Percentage
1–25	38,147	66.92%	38,147	66.92%
26–100	15,675	27.50%	53,822	94.41%
101–500	2,642	4.63%	56,464	99.05%
501–1000	354	0.62%	56,818	99.67%
> 1000	190	0.33%	57,008	100.00%
Total permits with yield information	57,008	--	--	--
Permits with no yield information	9,680	14.52%	66,688	--
Total permits	**66,688**	**(of total)**	--	--

Yield range (gpm)	New permits since 2002		Cumulative	
	Permits	Percentage	Permits	Percentage
1–25	14,691	57.36%	14,691	57.36%
26–100	9,012	35.19%	23,703	92.54%
101–500	1,654	6.46%	25,357	99.00%
501–1000	144	0.56%	25,501	99.56%
> 1000	112	0.44%	25,613	100.00%
Total permits with yield information	25,613	--	--	--
Permits with no yield information	2,234	8.02%	27,847	--
Total permits	**27,847**	**(of total)**	--	--

8.6.3 Groundwater permits by use: tables, figures, and matrix tables

Groundwater permit information categorized by use is presented in tables 8-6 through 8-9 and figures 8-1 through 8-7, and the matrix tables contained in the figures. This information was obtained from the SEO, MDNRC, SDDENR, and NDNR. In many cases, particularly with older permits, it is not known with any certainty whether a well or spring improvement was actually installed in association with a specific permit. Furthermore, existing facilities might have been abandoned after some time and are no longer being used beneficially. Any examination of permitted uses must explain how the permit data were processed and what the data actually represent. The permit data presented in the following two sections differ between the figures and the tables.

Tables 8-6 through 8-9 show the number of groundwater permits issued in Wyoming, Montana, South Dakota, and Nebraska by permitted use, regardless of permit status (sec. 8.4.1). This means that all permits issued are listed without evaluating if a well was installed. The tables list six single primary-use categories (municipal, domestic, industrial, irrigation, stock, and monitoring), an "other" category for all other single uses, and a "multi-use" category for permits that list more than one use (approximately 7 percent of all groundwater permits in the NERB are for multiple uses). The "other" category includes permits issued for "miscellaneous uses" and for minor uses such as test wells. The number of permits given for a single use, such as the 109 municipal-use permits in table 8-6, does not include "multi-use" or "other" permits, which may also allow municipal withdrawals. Additionally, tables 8-6 through 8-9 provide total permitted yields calculated by summation of all

Table 8-6. SEO groundwater permits in the NERB listed by intended use. Coalbed methane wells include any well that lists a CBM code including multi-use wells; multi-use wells shown do not include any well with a CBM code.

Well type	WSEO code	Total number of permits	New since 2002	Total permitted yield (gpm)	Total likely yield* (gpm)
Municipal	MUN	109	26	28,492	12,162
Domestic	DOM	6,539	1,737	86,212	68,006
Industrial	IND	629	44	108,100	31,783
Irrigation	IRR	319	48	156,635	97,393
Stock	STK	10,714	2,167	109,026	83,694
Monitor	MON	7,930	1,506	595	159
Other	MIS, blank	3,387	1,939	411,102	76,707
Coalbed methane	CBM	32,248	18,880	1,459,218	840,852
Multi-use	various	4,813	1,500	312,726	105,611
Total		**66,688**	**27,847**	**2,672,105**	**1,316,366**

*Includes only wells that are fully adjudicated, complete, and unadjudicated.

Table 8-7. Montana DNRC groundwater permits in the NERB listed by intended use.

Well type	Total number of permits	New since 2002	Total permitted yield (gpm)
Municipal	0	0	0
Domestic	23	2	211
Industrial	0	0	0
Irrigation	0	0	0
Stock	32	3	340
Monitoring	109	31	924
Other	21	1	0
Coalbed methane	1	0	0
Unknown	76	1	113
Total	**262**	**38**	**1,588**

Table 8-8. South Dakota DENR groundwater permits in the NERB listed by intended use. South Dakota data does not include yield information.

Well type	Total number of permits	New since 2002	Total permitted yield (gpm)
Municipal	0	0	------
Domestic	46	20	------
Industrial	1	0	------
Irrigation	0	0	------
Stock	8	0	------
Monitoring	13	0	------
Other	9	3	------
Total	**77**	**23**	**------**

Table 8-9. Nebraska DNR groundwater permits in the NERB listed by intended use.

Well type	Total number of permits	New since 2002	Total permitted yield (gpm)
Municipal	0	0	0
Domestic	0	0	0
Industrial	0	0	0
Irrigation	0	0	0
Stock	1	1	300
Monitoring	0	0	0
Other	0	0	0
Multi-use	0	0	0
Total	**1**	**1**	**300**

allowable yields and total likely yields determined by analysis of permit status.

Figures 8-1 through 8-7 show the number of "likely drilled wells," as determined by analysis of permit status (sec. 8.4.1) for each of the six primary-use categories and miscellaneous wells. This includes permits where one use is listed. For example, the number of municipal wells is determined by counting single-use "municipal" wells and any "multi-use" permits that include "municipal" as one of the permitted uses. Thus, multi-use wells are counted several times, once for each listed use.

Matrix tables contained in each of the figures present the number of all permits issued for each use combined in all states (fig. 3-1) regardless of permit status. This includes permits that list one-use and multi-use permits, for example, "municipal" as well as "multi-use" permits that include "municipal" as one of the permitted uses would be listed as "municipal" permits.

8.6.3.1 Groundwater permits by use: Tables 8-6 through 8-11

Tables 8-6 through 8-9 show that most groundwater permits in the NERB are for coalbed methane development, followed by livestock (stock) wells, and wells designated for monitoring.

Additionally, total likely yields (permitted yields from wells that are likely to be completed) constitute about 50 percent of the total permitted yields. A comparison of total likely yields to total permitted yields for each use suggests that a higher proportion of domestic (79 percent) and stock (77 percent) wells were completed and used beneficially than other types of wells.

Tables 8-10 and 8-11 are expanded summary tables for SEO permits that include municipal uses, and table 8-12 summarizes information on SWAP wells and springs that are used for both municipal and non-community public water supply. A brief discussion of the SWAP is provided in section 8.4.3.7. The SWAP provides some information beyond what is available in the SEO groundwater permits data.

8.6.3.2 Groundwater permit location maps and matrix tables, by use

Seven maps (figs. 8-1 through 8-7) were prepared for this study to illustrate the geospatial distribution of groundwater permits by use in the NERB. Only permits for wells that were likely to have been drilled (including abandoned wells) are included on figures 8-1 through 8-7. Groundwater permits in figures 8-2 through 8-7 are mapped by their date of issue: permits issued in 2002 or earlier are shown in blue, permits issued after 2002 are shown in red. Figures have been provided for the following permitted uses:

- Irrigation (fig. 8-1)
- Livestock (fig. 8-2)
- Municipal (fig. 8-3)
- Domestic (fig. 8-4)
- Industrial-use wells (fig. 8-5)
- Monitoring (fig. 8-6)
- Miscellaneous-use and other wells (fig. 8-7)
- USGS spring locations are shown on figure 7-2

In order to evaluate "recent" groundwater development that occurred since the previous water basin plans (HKM Engineering, 2002a, b), figures 8-1 through 8-7 differentiate groundwater permits issued after 2002. As with earlier groundwater rights, most permits issued after 2002 continue to target Tertiary hydrogeologic units.

Matrix tables that correlate ranges of well depths and yields for all permits issued are also provided in figures 8-1 through 8-7. Consistent with table 8-5, the depth versus yield tables show that by far the most permits issued in the NERB are for 0–25 gpm across all depth ranges. In addition, the insert tables show that fewer wells are permitted for increasingly higher yields across all depth ranges. Because only permits for wells that were likely to have been drilled (status of fully adjudicated, complete, unadjudicated, and abandoned) are shown on figures 8-1 through 8-7, the number of permits on the insert matrix tables does not match the number of permits depicted on the maps.

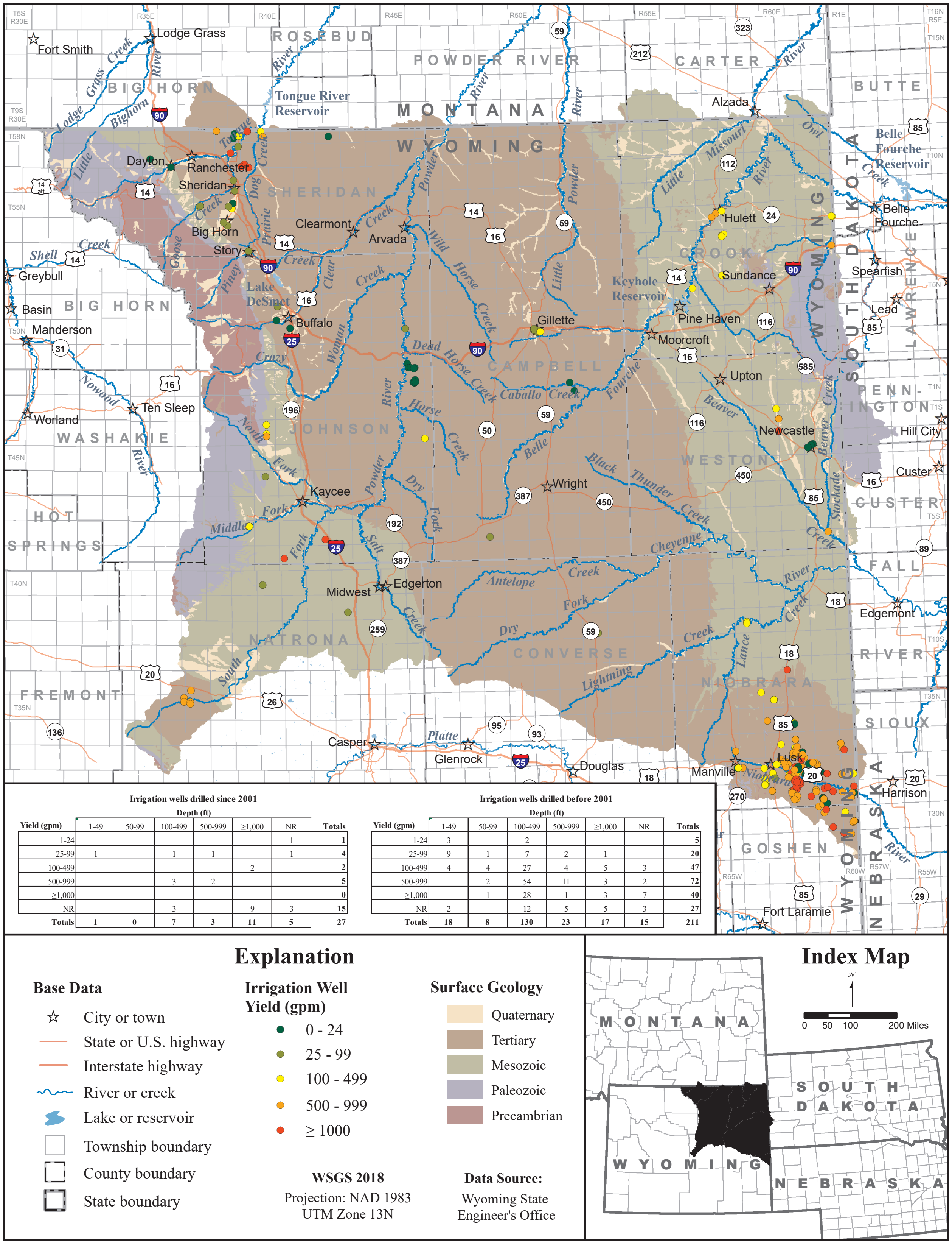
Figure 5-11 shows the distribution of SWAP wells used for municipal and other public supply. Because public supply is one of the most important uses of groundwater resources, a more comprehensive compilation was performed for the SEO permit data and related WDEQ SWAP data on municipal and non-community public groundwater supplies.

8.6.3.3 Irrigation-use permits

Tables 8-6 through 8-9 list 319 groundwater permits for irrigation use (IRR) in the NERB, all located in Wyoming. Figure 8-1 shows the distribution of likely drilled irrigation wells. Most irrigation wells are located in the High Plains aquifer system of the Upper Niobrara River Basin. The depth versus yield tables in figure 8-1 show that most irrigation well permits that list depth were permitted for depths of 100–499 ft and include a wide range of yields. Table 8-6 and the matrix tables in figure 8-1 illustrate that most irrigation permits in the NERB were issued before 2003.

8.6.3.4 Livestock-use permits

Tables 8-6 through 8-9 show 10,755 groundwater permits have been issued solely for livestock use (STK) in the NERB. Figure 8-2 shows the distribution of likely drilled stock wells in the NERB issued since 2002. Stock wells are sited most densely in the eastern two-thirds of the NERB and in a broad band beginning along the upper reaches of Crazy Woman Creek and extending northwest into the Tongue River Basin. Most stock wells are completed in outcrops of Tertiary and Cretaceous units. The depth versus yield tables in figure 8-2 show that the largest number of total permits and permits issued since 2002 are for depths under 500 ft and for yields less than 25 gpm.



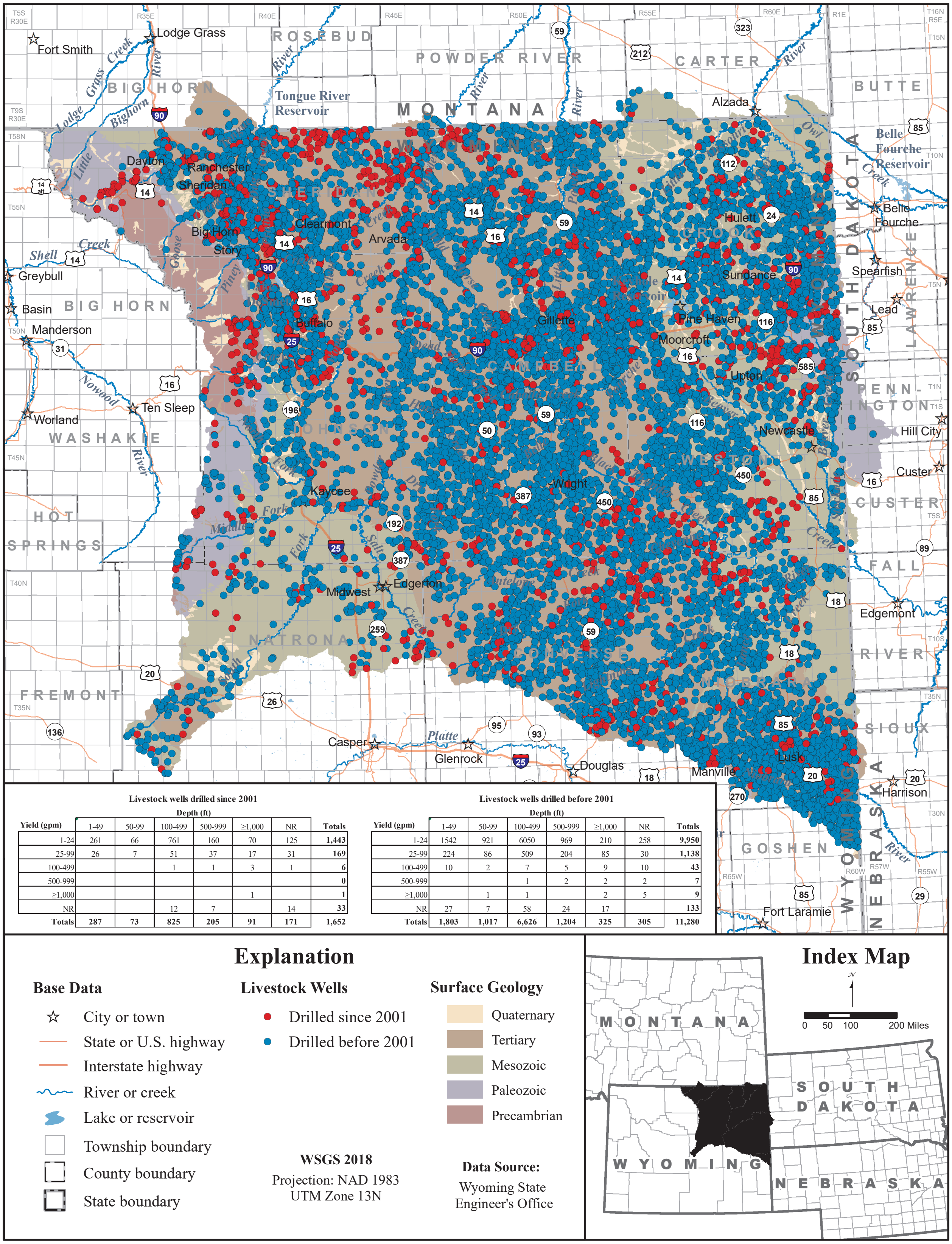
Irrigation wells drilled since 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24						1	**1**
25-99	1		1	1		1	**4**
100-499					2		**2**
500-999			3	2			**5**
≥1,000							**0**
NR			3		9	3	**15**
Totals	**1**	**0**	**7**	**3**	**11**	**5**	**27**

Irrigation wells drilled before 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	3		2				**5**
25-99	9	1	7	2	1		**20**
100-499	4	4	27	4	5	3	**47**
500-999		2	54	11	3	2	**72**
≥1,000		1	28	1	3	7	**40**
NR	2		12	5	5	3	**27**
Totals	**18**	**8**	**130**	**23**	**17**	**15**	**211**

Figure 8-1. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled irrigation wells, NERB.



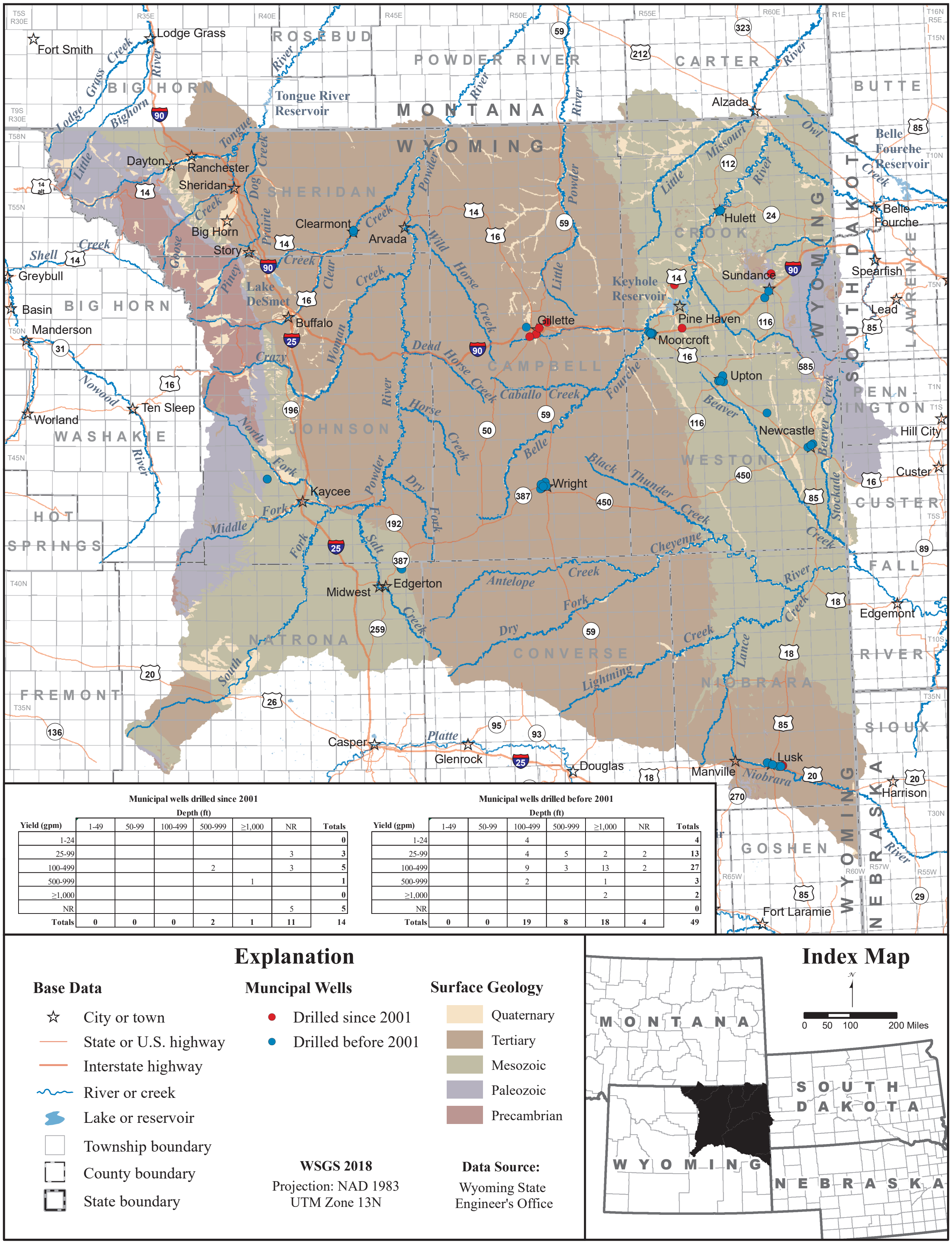
Livestock wells drilled since 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	261	66	761	160	70	125	**1,443**
25-99	26	7	51	37	17	31	**169**
100-499			1	1	3	1	**6**
500-999							**0**
≥1,000					1		**1**
NR			12	7		14	**33**
Totals	**287**	**73**	**825**	**205**	**91**	**171**	**1,652**

Livestock wells drilled before 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1542	921	6050	969	210	258	**9,950**
25-99	224	86	509	204	85	30	**1,138**
100-499	10	2	7	5	9	10	**43**
500-999			1	2	2	2	**7**
≥1,000		1	1		2	5	**9**
NR	27	7	58	24	17		**133**
Totals	**1,803**	**1,017**	**6,626**	**1,204**	**325**	**305**	**11,280**

Figure 8-2. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled livestock wells, NERB.



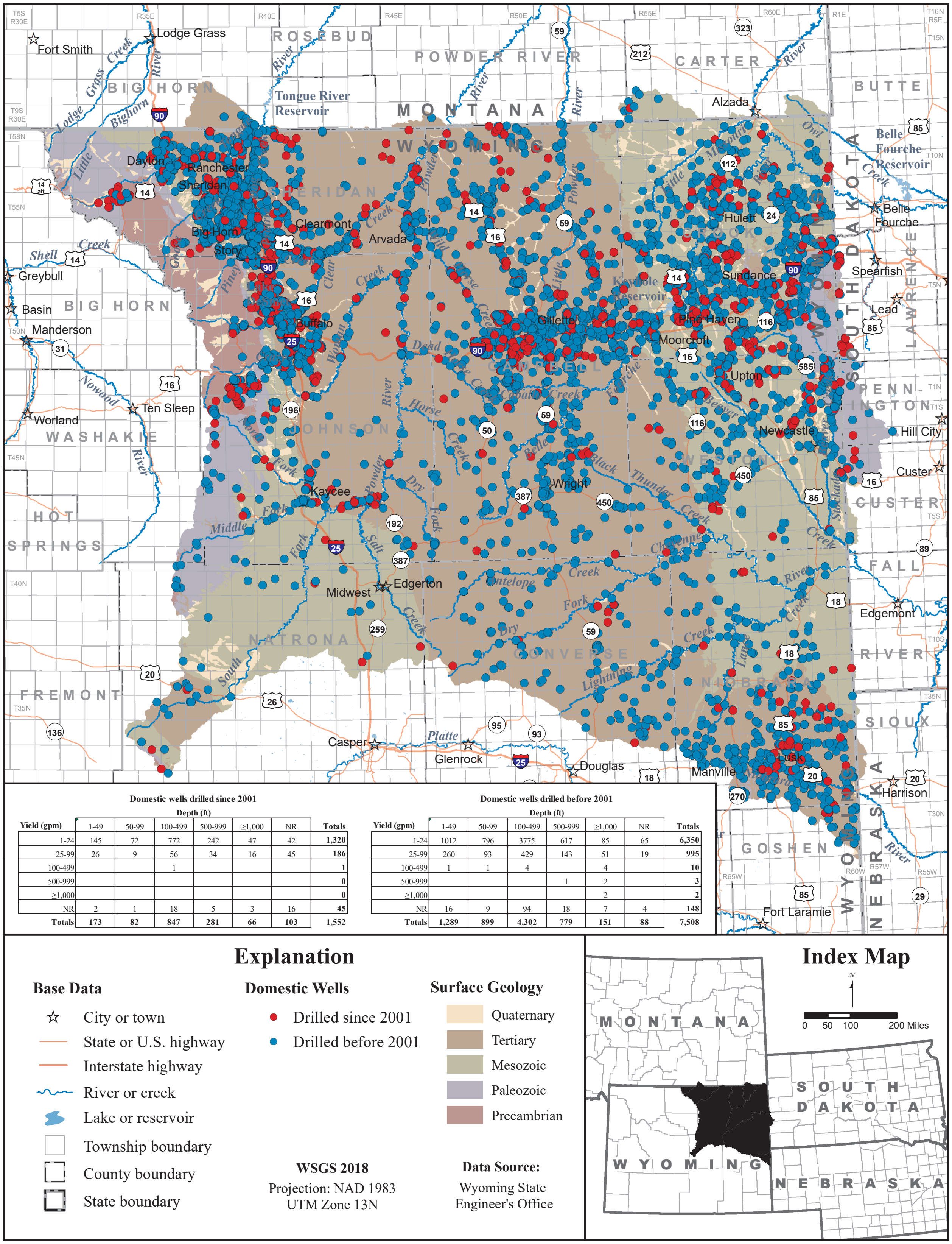
Municipal wells drilled since 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99						3	3
100-499				2		3	5
500-999					1		1
≥1,000							0
NR						5	5
Totals	0	0	0	2	1	11	14

Municipal wells drilled before 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24			4				4
25-99			4	5	2	2	13
100-499			9	3	13	2	27
500-999			2		1		3
≥1,000					2		2
NR							0
Totals	0	0	19	8	18	4	49

Figure 8-3. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled municipal wells, NERB.



Domestic wells drilled since 2001

Depth (ft)

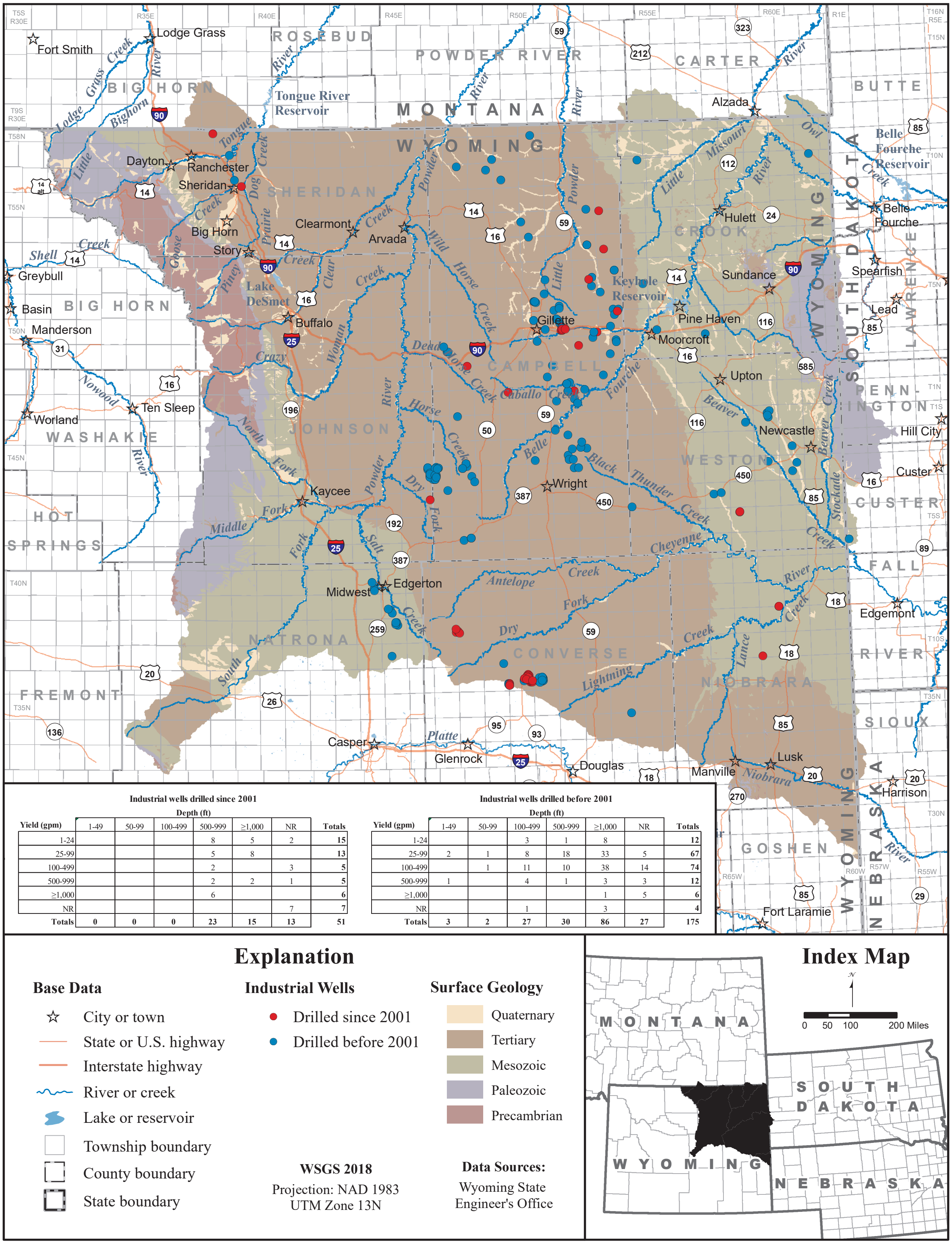
Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	145	72	772	242	47	42	**1,320**
25-99	26	9	56	34	16	45	**186**
100-499			1				**1**
500-999							**0**
≥1,000							**0**
NR	2	1	18	5	3	16	**45**
Totals	**173**	**82**	**847**	**281**	**66**	**103**	**1,552**

Domestic wells drilled before 2001

Depth (ft)

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	1012	796	3775	617	85	65	**6,350**
25-99	260	93	429	143	51	19	**995**
100-499	1	1	4		4		**10**
500-999				1	2		**3**
≥1,000					2		**2**
NR	16	9	94	18	7	4	**148**
Totals	**1,289**	**899**	**4,302**	**779**	**151**	**88**	**7,508**

Figure 8-4. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled domestic wells, NERB.



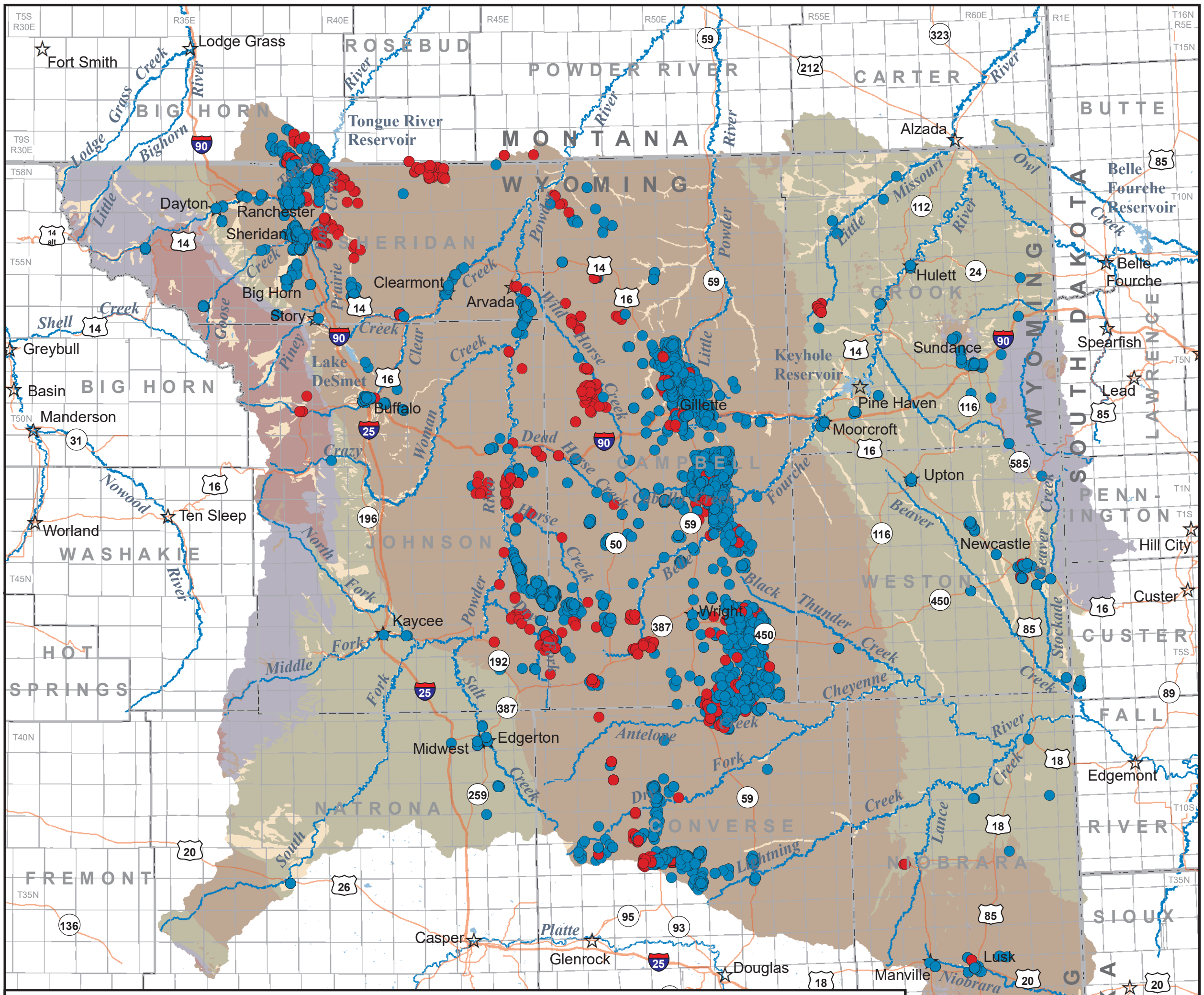
Industrial wells drilled since 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24				8	5	2	**15**
25-99				5	8		**13**
100-499				2		3	**5**
500-999				2	2	1	**5**
≥1,000				6			**6**
NR						7	**7**
Totals	**0**	**0**	**0**	**23**	**15**	**13**	**51**

Industrial wells drilled before 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24			3	1	8		**12**
25-99	2	1	8	18	33	5	**67**
100-499		1	11	10	38	14	**74**
500-999	1		4	1	3	3	**12**
≥1,000					1	5	**6**
NR			1		3		**4**
Totals	**3**	**2**	**27**	**30**	**86**	**27**	**175**

Figure 8-5. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled industrial wells, NERB.



Monitoring wells drilled since 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	3	1	1	1	3	1	**10**
25-99		5					**5**
100-499							**0**
500-999							**0**
≥1,000							**0**
NR	202	97	292	151	41	22	**805**
Totals	**205**	**103**	**293**	**152**	**44**	**23**	**820**

Monitoring wells drilled before 2001

Yield (gpm)	Depth (ft) 1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	9	6	26				**41**
25-99		6	2		2		**10**
100-499							**0**
500-999							**0**
≥1,000							**0**
NR	1794	414	1925	864	47	41	**5,085**
Totals	**1,803**	**426**	**1,953**	**864**	**49**	**41**	**5,136**

Explanation

Base Data

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

Monitoring Wells

● Drilled since 2001
● Drilled before 2001

Surface Geology

Quaternary
Tertiary
Mesozoic
Paleozoic
Precambrian

WSGS 2018

Projection: NAD 1983
UTM Zone 13N

Data Sources:

Wyoming State
Engineer's Office

Index Map

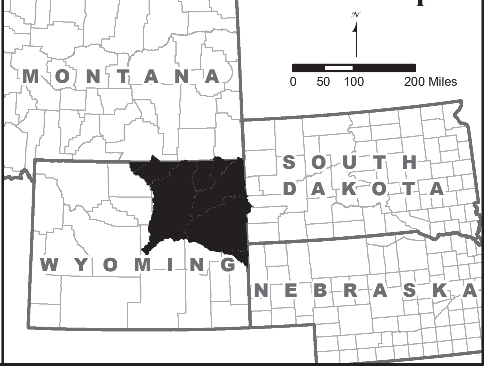
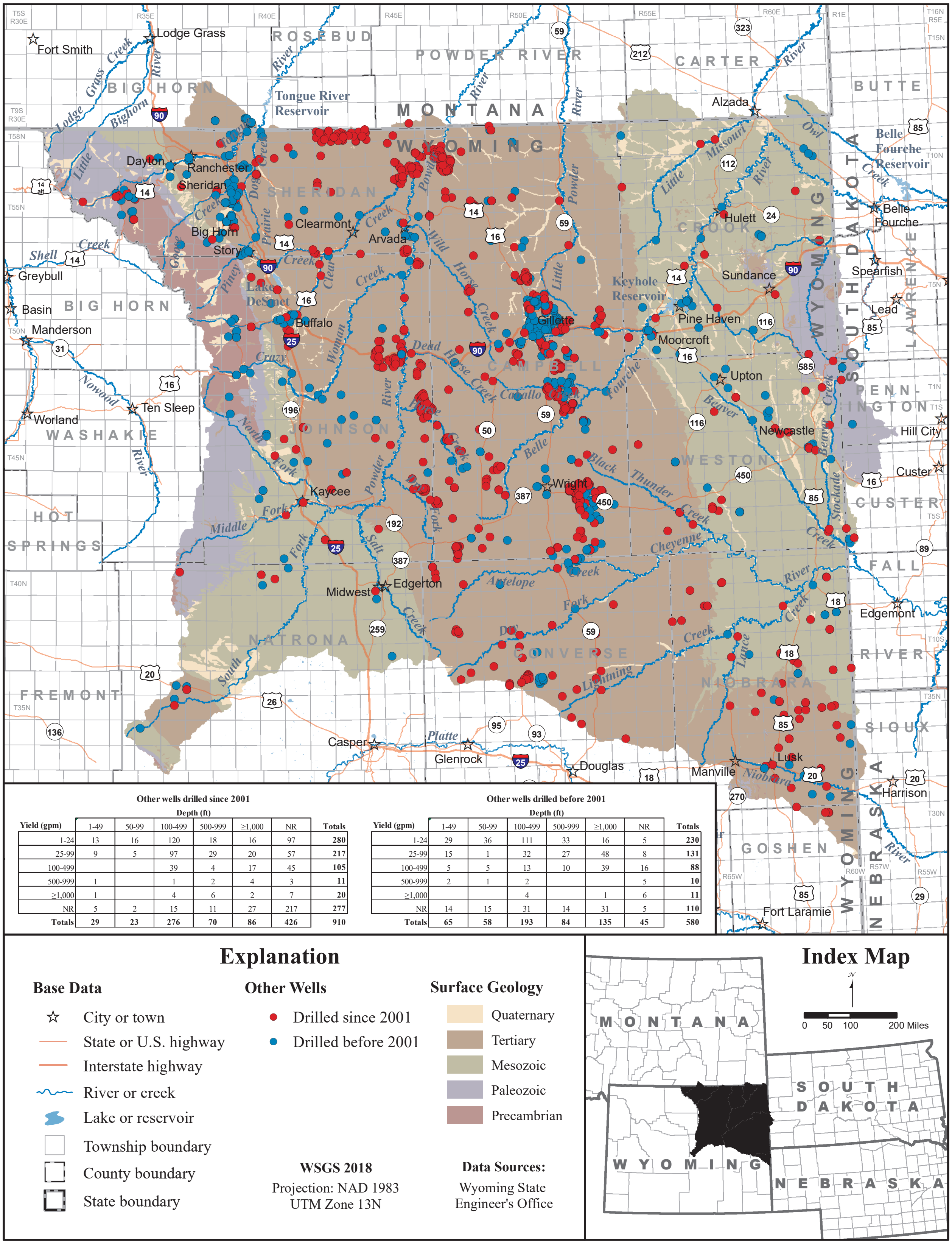


Figure 8-6. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled monitoring wells, NERB.



Other wells drilled since 2001

Depth (ft)

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	13	16	120	18	16	97	**280**
25-99	9	5	97	29	20	57	**217**
100-499			39	4	17	45	**105**
500-999	1		1	2	4	3	**11**
≥1,000	1		4	6	2	7	**20**
NR	5	2	15	11	27	217	**277**
Totals	**29**	**23**	**276**	**70**	**86**	**426**	910

Other wells drilled before 2001

Depth (ft)

Yield (gpm)	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	29	36	111	33	16	5	**230**
25-99	15	1	32	27	48	8	**131**
100-499	5	5	13	10	39	16	**88**
500-999	2	1	2			5	**10**
≥1,000			4		1	6	**11**
NR	14	15	31	14	31	5	**110**
Totals	**65**	**58**	**193**	**84**	**135**	**45**	580

Figure 8-7. Wyoming SEO, Montana DNRC, South Dakota DENR, and Nebraska DNR permitted and drilled other wells, NERB.

8.6.3.5 Municipal-use permits

All 109 groundwater permits issued solely for municipal use (MUN) in the NERB are in Wyoming (tables 8-6 through 8-9). Figure 8-3 shows the spatial distribution of likely drilled municipal wells. Most municipal permits issued since 2002 do not contain depth data. No municipal-use permits are listed in neighboring states.

Tables 8-10 and 8-11 distinguish 109 municipal-use groundwater permits on file with the SEO by status. Table 8-10 summarizes selected information on 47 municipal-use permits that have been fully adjudicated. Table 8-10 includes available information on permitted yield, well depth, depth of the producing interval, and the producing hydrogeologic unit. Only one permit in table 8-8 is for multiple uses. Because the "fully adjudicated" permit status indicates that the well has been inspected, the information in table 8-10 is presumed to be accurate. The wells in table 8-10 produce water from alluvial and bedrock aquifers (pl. 2). Information on producing intervals was obtained from SWAP data, WWDC consultant reports, and SEO data.

Table 8-11 summarizes selected information on 78 SEO municipal well permits listed as incomplete or have no status listed. Table 8-11 includes available information on permitted yield and well depth. Eleven of the permits in table 8-11 are for multiple uses. The wells in table 8-11 produce water from alluvial and bedrock aquifers (pl. 2).

While cancelled permits may or may not be associated with a completed well, abandoned status generally refers to a previously existing well.

8.6.3.6 Domestic-use permits

Domestic water withdrawals include non-community public water systems and rural domestic users. Tables 8-6 through 8-9 show that groundwater permits for domestic use (DOM) outnumber permits for all other non-CBM uses except livestock and monitoring wells.

Figure 8-4 shows the distribution of likely drilled domestic-use permits. Most domestic wells are in rural areas outside of municipalities in Johnson, Sheridan, Campbell, Crook, Weston, and Niobrara counties. Most wells are completed in Tertiary, Cretaceous, and Paleozoic geologic units. The depth versus yield tables in figure 8-4 show that basin wide, the largest percentage of permits issued after 2002 allow well depths up to 499 ft and yields up to 25 gpm. Around 2 percent of domestic-use permits do not provide any recorded depth information.

8.6.3.7 Source Water Assessment Program (SWAP) wells and springs

The SWAP, a component of the federal Safe Drinking Water Act, is designed to help states protect public water systems (PWS) and applies to both municipal and non-community public systems. The voluntary program, administered by the WDEQ Water Quality Division (WQD), encourages the development of source-water assessments and Wellhead Protection Plans (WHP) for groundwater PWS. A source-water assessment entails determining the source-water contributing area, inventorying potential sources of contamination to the PWS, determining the susceptibility of the PWS to identified potential contaminants, and summarizing the information in a report. An important aspect of these reports relative to this study is that the producing hydrogeologic unit is commonly identified. As discussed in section 5.7.4, the individual PWS reports provide valuable information on recharge areas, resource vulnerability, and local sources of potential contaminants for specific groundwater sources. The development and implementation of SWAP and WHP assessments and plans are ongoing throughout Wyoming. Additional information is available on the WDEQ website, http://deq.wyoming.gov/wqd/source-water-wellhead/.

Table 8-12 provides SEO water right permit number, yield, producing unit, and depth data for 169 SWAP wells in the NERB. The SEO permit numbers shown can be correlated with the wells shown in tables 8-10 and 8-11. Most wells in the SWAP database produce groundwater from Tertiary, Cretaceous, and Paleozoic units (table 8-12).

Figure 5-11 shows the geospatial distribution of SWAP wells in the NERB and their relative susceptibility to potential contaminants.

8.6.3.8 Industrial use

Tables 8-6 and 8-8 list 629 Wyoming permits and 1 South Dakota permit for industrial (IND) use. Primary industrial uses in the NERB have included construction company usage, as well as aggregate and gravel mining. The SEO database does not identify specific industrial uses.

8.6.3.8.1 Energy production

Groundwater associated with oil, gas, and coal production includes "produced water" withdrawn as a byproduct of extraction from hydrocarbon reservoirs and water utilized in the production and refining of energy resources. In some cases, produced water is used in production and refining operations; in others, water for operations is obtained from surface or underground sources. Some water plans (e.g., the

Table 8-10. SEO fully adjudicated municipal well permits in the NERB.

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	Hydrogeologic unit	Multi-use	Depth of producing interval (ft)
Clearmont	CLEARMONT WATER WELL #3	P1666.0W	35	172	Fully Adjudicated			90–172
Clearmont	CLEARMONT #1	P37666.0W	30	522	Fully Adjudicated	Wasatch		492–515
Clearmont	CLEARMONT #2	P45802.0W	70	1,447	Fully Adjudicated	Ft. Union		1,286–1,320
Clearmont	ENL CLEARMONT WATER WELL #3	P71412.0W	120	172	Fully Adjudicated			143–172
Edgerton	EDGERTON #6	P44002.0W	40	0	Fully Adjudicated			2,000–2,087
Edgerton	EDGERTON WATER WELL #5	P6319.0W	35	0	Fully Adjudicated			Unknown
Hulett	HULETT ARTESIAN #2	P118.0G	150	690	Fully Adjudicated			590–690
Hulett	HULETT ARTESIAN WELL #1	P31.0C	150	620	Fully Adjudicated			600–620
Hulett	HULETT WELL #3	P56489.0W	150	772	Fully Adjudicated			696–740
Kaycee	KAYCEE WELL #1	P69394.0W	25	1,612	Fully Adjudicated			1,346–1,612
Kaycee	KAYCEE WELL #2	P72663.0W	175	2,000	Fully Adjudicated			710–1,000
Lusk	TOWN OF LUSK #1 WELL	P285.0G	350	132	Fully Adjudicated			70–130
Lusk	TOWN OF LUSK #3	P286.0G	280	151	Fully Adjudicated			70–150
Lusk	TOWN OF LUSK #4 WELL	P483.0C	285	140	Fully Adjudicated			70–140
Lusk	TOWN OF LUSK #7	P59002.0W	400	460	Fully Adjudicated			230–258
Lusk	TOWN LUSK #8	P59003.0W	800	484	Fully Adjudicated			230–270
Lusk	ENL TOWN OF LUSK #1	P76207.0W	550	132	Fully Adjudicated			70–130
Lusk	ENL TOWN OF LUSK #3	P76208.0W	220	151	Fully Adjudicated			70–150
Lusk	ENL TOWN OF LUSK #7	P76209.0W	350	460	Fully Adjudicated			230–258
Lusk	ENL TOWN OF LUSK #8	P78254.0W	100	484	Fully Adjudicated			230–270
Moorcroft	MOORCROFT #5	P33968.0W	30	485	Fully Adjudicated			310–470
Moorcroft	ENL MOORCROFT #5	P42845.0W	25	485	Fully Adjudicated			370–466
Moorcroft	MOORCROFT #6	P43549.0W	90	760	Fully Adjudicated			600–690
Moorcroft	MOORCROFT #1	P990.0W	25	500	Fully Adjudicated			200–Unknown
Moorcroft	MOORCROFT #2	P991.0W	20	400	Fully Adjudicated			200–Unknown
Moorcroft	MOORCROFT #3	P992.0W	20	385	Fully Adjudicated			175–Unknown
Moorcroft	MOORCROFT #4	P993.0W	30	485	Fully Adjudicated			135–Unknown

Table 8-10. continued

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	Hydrogeologic unit	Multi-use	Depth of producing interval (ft)
Newcastle	MUNICIPAL WELL #3	P1317.0W	200	2,872	Fully Adjudicated			2,211–Unknown
Newcastle	NEWCASTLE ARTESIAN WELL #1	P38.0G	1,400	2,638	Fully Adjudicated			2,612–2,638
Newcastle	NEWCASTLE #2 WELL	P389.0W	475	3,028	Fully Adjudicated			Unknown
Newcastle	NEWCASTLE #4	P39352.0W	500	3,245	Fully Adjudicated			2,743–2,120
Osage	OSAGE #3	P46982.0W	1,100	3,135	Fully Adjudicated		yes	2,716–3,135
Sundance	LOAFMAN WELL #1	P2520.0W	15	140	Fully Adjudicated			16–140
Sundance	LOAFMAN WELL #2	P2521.0W	15	115	Fully Adjudicated			6–115
Sundance	HARD WATER #5	P2523.0W	197	440	Fully Adjudicated			313–320
Upton	TOWN OF UPTON WELL #2	P28335.0W	205	3,162	Fully Adjudicated			2,900–3,162
Upton	TOWN OF UPTON WELL #3	P28336.0W	35	804	Fully Adjudicated			Unknown
Upton	TOWN OF UPTON WELL #4	P28337.0W	205	-1	Fully Adjudicated			Unknown
Upton	TOWN OF UPTON WELL #5	P28338.0W	35	545	Fully Adjudicated			Unknown
Upton	UPTON WELL #6	P62883.0W	200	3,310	Fully Adjudicated			2,820–3,310
Upton	ENL TOWN OF UPTON WELL #2	P63481.0W	120	3,162	Fully Adjudicated			2,900–3,162
Upton	ENL TOWN OF UPTON WELL #4	P63482.0W	170	3,193	Fully Adjudicated			2,724–3,193
Upton	UPTON WELL #7	P98208.0W	200	0	Fully Adjudicated			2,810–3,308
Wright	RJ 2	P46664.0W	250	2,660	Fully Adjudicated			Unknown
Wright	RJ 3	P46696.0W	225	2,730	Fully Adjudicated			Unknown
Wright	RJ 5	P48091.0W	400	2,700	Fully Adjudicated			1,232–2,679
Wright	RJ 4	P71834.0W	300	3,015	Fully Adjudicated			1,222–2,707
Totals			**10,802**					

Table 8-11. SEO municipal well permits listed with a status other than Fully Adjudicated in the NERB.

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	New since 2002	Multiple-use well
Buffalo	BUFFALO UNDERGROUND WATER SUPPLY #1	P1.0G	990	18	Incomplete		
Buffalo	CLEAR CREEK #2	P42.0W	790	25	Incomplete		
Buffalo	C. VANCE LUCAS WELL #1	P633.0W	25	239	Incomplete		Yes
Buffalo	FRANK E. LUCAS WELL #1	P634.0W	100	175	Incomplete		Yes
Dayton	DAYTON #1	P146036.0W	225	2,600	Incomplete		
Edgerton	EDGERTON PARSONS #1	P508.0C	10.9	130	Incomplete		
Gillette	ENL. S-17	P193939.0W	110	Unknown	Complete	Yes	
Gillette	ENL. S-27	P193941.0W	35	Unknown	Complete	Yes	
Gillette	SUNBURST #1 (DEEPENED)	P1015.0W	15	200	Incomplete		
Gillette	S-23	P101734.0W	150	2,252	Incomplete		
Gillette	S-24	P102212.0W	170	2,430	Incomplete		
Gillette	S-25	P102213.0W	125	2,469	Incomplete		
Gillette	FOX HILLS #5	P108708.0W	500	4,170	Incomplete		
Gillette	S-27	P109197.0W	150	Unknown	Incomplete		
Gillette	S-26	P109198.0W	150	2,515	Incomplete		
Gillette	GILLETTE #P-1	P1220.0W	90	500	Incomplete		
Gillette	GILLETTE # H 11	P1221.0W	80	500	Incomplete		
Gillette	M-10	P172432.0W	1,470	2,524	Incomplete		
Gillette	M-9	P172433.0W	1,470	2,523	Incomplete	Yes	
Gillette	ENL. S-20	P190124.0W	50	Unknown	Incomplete	Yes	
Gillette	ENL. S-19	P193940.0W	215	Unknown	Incomplete	Yes	
Gillette	MADISON 13	P204034.0W	1,600	Unknown	Incomplete	Yes	
Gillette	MADISON 14	P204035.0W	1,600	Unknown	Incomplete	Yes	
Gillette	MADISON 15	P204036.0W	1,600	Unknown	Incomplete	Yes	
Gillette	FOX HILLS #3	P30005.0W	340	4,436	Incomplete		Yes
Gillette	S-18	P41830.0W	250	1,522	Incomplete		

Table 8-11. continued

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	New since 2002	Multiple-use well
Gillette(cont.)							
Gillette	S-19	P41831.0W	130	Unknown	Incomplete		
Gillette	GILLETTE #H-26	P42002.0W	83	301	Incomplete		
Gillette	GILLETTE #H-27	P42003.0W	80	382	Incomplete		
Gillette	CITY OF GILLETTE S-9	P42004.0W	271	1,672	Incomplete		
Gillette	CITY OF GILLETTE S-10	P42005.0W	170	2,350	Incomplete		
Gillette	CITY OF GILLETTE S-11	P42006.0W	125	2,323	Incomplete		
Gillette	CITY OF GILLETTE S-12	P42007.0W	125	2,295	Incomplete		
Gillette	S-17	P42010.0W	220	Unknown	Incomplete		
Gillette	FOXHILLS #4	P60723.0W	550	4,350	Incomplete		
Gillette	ENL FOX HILLS #3	P66144.0W	210	4,436	Incomplete		
Gillette	ENL FOX HILLS #3	P85458.0W	950	4,436	Incomplete		Yes
Gillette	S-21	P99185.0W	150	2,250	Incomplete		
Gillette	S-22	P99186.0W	120	2,315	Incomplete		
Gillette	ENL. S-12	P190123.0W	100	Unknown	Unadjudicated	Yes	
Gillette	ENL. FOX HILLS NO. 5	P190131.0W	25	Unknown	Unadjudicated	Yes	
Gillette	S-20	P42985.0W	160	2,429	Unadjudicated		
Gillette/Moorcroft	M-1	P56867.0W	800	2,767	Incomplete		Yes
Gillette/Moorcroft	M-2	P56868.0W	800	2,614	Incomplete		Yes
Gillette/Moorcroft	M-3	P56869.0W	800	3,001	Incomplete		Yes
Gillette/Moorcroft	M-4	P56870.0W	900	2,525	Incomplete		Yes
Gillette/Moorcroft	M-5	P56871.0W	800	3,005	Incomplete		Yes
Gillette/Moorcroft	M-6	P56872.0W	800	3,005	Incomplete		Yes
Gillette/Moorcroft	M-7	P56873.0W	750	3,006	Incomplete		Yes
Gillette/Moorcroft	M-8	P56874.0W	750	3,008	Incomplete		Yes
Gillette/Moorcroft	ENL. M-3	P190132.0W	50	Unknown	Unadjudicated	Yes	

Table 8-11. continued

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	New since 2002	Multiple-use well
Hulett	HULETT #4	P104685.0W	300	1,923	Incomplete		
Lusk	LUSK WELL NO. 10	P191344.0W	400	579	Complete	Yes	
Lusk	LUSK WELL NO. 9	P191343.0W	450	Unknown	Unadjudicated		
Manville	MANVILLE #3	P104368.0W	65	Unknown	Incomplete		
Manville	MANVILLE WELL #1	P594.0C	150	Unknown	Incomplete		
Manville	MANVILLE WELL #2	P595.0C	100	Unknown	Incomplete		
Moorcroft	MOORCROFT MADISON WELL	P165471.0W	600	3,742	Complete	Yes	
Moorcroft	MOORCROFT #8	P104085.0W	55	1,204	Incomplete		
Moorcroft	MOORCROFT WELL NO. 9	P187371.0W	75	1,118	Incomplete		
Moorcroft	MOORCROFT WELL NO. 10	P187372.0W	75	1,097	Incomplete		
Moorcroft	MOORCROFT #7	P92166.0W	0	800	Incomplete		
Newcastle	CARLSON #1	P607.0W	650	2,738	Incomplete		Yes
Pine Haven	PINE HAVEN NO. 2	P147769.0W	250	Unknown	Incomplete		
Pine Haven	ENL. PINE HAVEN NO. 2	P185386.0W	100	Unknown	Incomplete		
Pine Haven	KEYHOLE #1	P78993.0W	150	4,110	Incomplete		
Sundance	COLE NO. 3 C WELL	P191655.0W	200	610	Complete	Yes	
Sundance	BEAGLE #1	P499.0G	100	33	Incomplete		Yes
Sundance	SUNDANCE #6	P72179.0W	400	1,184	Incomplete		Yes
Upton	UPTON NO. 8 WELL	P175186.0W	500	Unknown	Undefined	Yes	
Wright	RJ-6	P145417.0W	330	2,762	Complete		
Wright	ENL RJ-2	P189673.0W	0	Unknown	Complete	Yes	
Wright	2ND ENL RJ-3	P189674.0W	0	Unknown	Complete	Yes	
Wright	ENL RJ-4	P189675.0W	0	Unknown	Complete	Yes	

Table 8-11. continued

Municipality or community	Well name	WSEO permit number	Permit yield (gpm)	Well depth (ft)	Permit status	New since 2002	Multiple-use well
Wright (cont.)							
Wright	ENL RJ-5	P189676.0W	0	Unknown	Complete	Yes	
Wright	ENL RJ-6	P189677.0W	0	Unknown	Complete	Yes	
Wright	ENL RJ-2 WELL	P101356.0W	75	2,660	Incomplete		
Wright	RJ-7	P186050.0W	500	Unknown	Incomplete		
Totals			**27,755**				

Table 8-12. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply in the NERB.

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Buffalo							
	BUFFALO, CITY OF	5600005-103	P9110W			Well	
Clearmont							
	CLEARMONT, TOWN OF	5600013-101	P37666W	30		Well	
	CLEARMONT, TOWN OF	5600013-102	P45802W	70		Well	
Edgerton							
	EDGERTON, TOWN OF	5600017-101	P44002W	40		Well	
	EDGERTON, TOWN OF	5600017-102	P6319W	35		Well	
Gillette							
	GILLETTE, CITY OF	5600019-101	P24347W		3,479	Well	Fox Hills Fm
	GILLETTE, CITY OF	5600019-102	P25111W		8,509	Well	Fox Hills/Fort Union Fm
	GILLETTE, CITY OF	5600019-103	P30005W		4,437	Well	Lance Fm/Fox Hills Fm
	GILLETTE, CITY OF	5600019-104	P60723W		4,350	Well	Lance Fm/Fox Hills Fm
	GILLETTE, CITY OF	5600019-105	P42004W		1,208	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-106	P42005W		2,350	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-107	P42007W		2,350	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-108	P42010W		2,334	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-109	P41830W		1,850	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-110	P41831W		1,750	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-111	P42985W	160	2,429	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-112	P42006W		2,323	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-113	P69300W		2,767	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-114	P69301W		2,614	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-115	P69302W		3,001	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-116	P69303W		2,525	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-117	P69304W		3,005	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-118	P69305W		3,005	Well	Madison Limestone

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Gillette (cont.)							
	GILLETTE, CITY OF	5600019-119	P69306W		3,006	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-120	P69307W		3,008	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-121	P69308W		2,511	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-122	P69309W		2,514	Well	Madison Limestone
	GILLETTE, CITY OF	5600019-123	P99185W		2,250	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-124	P99186W		2,315	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-125	P101734W		2,252	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-126	P102212W		2,430	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-127	P102213W		2,469	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-128	P109198W		2,515	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-129	P109197W		25,35	Well	Fort Union Fm
	GILLETTE, CITY OF	5600019-130	P108708W		4,170	Well	Lance Fm/Fox Hills Fm
Hulett							
	HULETT, TOWN OF	5600026-101	P83422W		1,923	Well	Pahasapa Limestone
Kaycee							
	KAYCEE, TOWN OF	5600196-101	P72663W	175	1,200	Well	Madison Limestone and Tensleep Fm
	KAYCEE, TOWN OF	5600196-102	P69394W	25	1,700	Well	Madison Limestone and Tensleep Fm
Moorcroft							
	MOORCROFT, TOWN OF	5600037-102	P33968W	30	486	Well	Lance Fm
	MOORCROFT, TOWN OF	5600037-103	P990W	25	500	Well	Lance Fm
	MOORCROFT, TOWN OF	5600037-104	P43549W	90	760	Well	Lance Fm
	MOORCROFT, TOWN OF	5600037-105	P104085W		1,204	Well	Lance Fm
Newcastle							
	NEWCASTLE, CITY OF	5600256-101	P38G	1,400	2,638	Well	Madison Limestone
	NEWCASTLE, CITY OF	5600256-102	P389W	475	3,022	Well	Madison Limestone

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Newcastle (cont.)							
	NEWCASTLE, CITY OF	5600256-103	P1317W	200		Well	Madison Limestone
	NEWCASTLE, CITY OF	5600256-104	P39352W	500	3,121	Well	Madison Limestone
Pine Haven							
	PINE HAVEN, TOWN OF	5600191-101	P9493W	0.42	717	Well	Newcastle Fm
	PINEY CREEK GROCERY	5601145-101	P15801W		58	Well	
Sundance							
	SUNDANCE, CITY OF	5600055-101	P1544W		517	Well	Minnelusa Fm and Pahasapa Limestone
	SUNDANCE, CITY OF	5600055-102	P8377W		1,123	Well	Minnelusa Fm and Pahasapa Limestone
	SUNDANCE, CITY OF	5600055-103	P50484W		1,236	Well	Minnelusa Fm and Pahasapa Limestone
	SUNDANCE, CITY OF	5600055-104	P72179W		1,184	Well	Minnelusa Fm and Pahasapa Limestone
Upton							
	UPTON, TOWN OF	5600140-101	P28335W	205	3,161	Well	Madison Limestone
	UPTON, TOWN OF	5600140-102	P28337W	205	3,193	Well	Madison Limestone
	UPTON, TOWN OF	5600140-103	P28338W	35	545	Well	Newcastle Fm
	UPTON, TOWN OF	5600140-104	P98208W	200	3,308	Well	Madison Limestone
	UPTON, TOWN OF	5600140-105			3,300		Madison Limestone
Wright							
	WRIGHT WATER & SEWER DISTRICT	5600136-101	P46664W	250	2,660	Well	Fort Union Fm
	WRIGHT WATER & SEWER DISTRICT	5600136-102	P46696W	225	2,730	Well	Fort Union Fm
	WRIGHT WATER & SEWER DISTRICT	5600136-103	P71834W	300	3,015	Well	Fort Union Fm
	WRIGHT WATER & SEWER DISTRICT	5600136-104	P48091W	400	2,700	Well	Fort Union Fm
Unknown							
	AMERICAN COLLOID-COLONY EAST	5601235-101	P130433W		820	Well	Falls River Sandstone

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Unknown (cont.)							
	AMERICAN COLLOID-COLONY WEST	5601236-101	P129078W		880	Well	Falls River Sandstone
	AMERICAN COLLOID-COLONY WEST	5601236-102	P145936W	50	775	Well	Falls River Sandstone
	ANTELOPE COAL COMPANY	5601374-101	P56958W		2,620	Well	Ft. Union Fm
	ANTELOPE MOBILE HOME PARK	5600131-101			1,000	Well	Wasatch Fm
	ANTELOPE MOBILE HOME PARK	5600131-102			750	Well	Wasatch Fm
	ANTELOPE VALLEY	5600251-101	P37361W	90	1,305	Well	Wasatch Fm
	ANTELOPE VALLEY	5600251-102	P64374W	125	1,672	Well	Wasatch Fm
	ANTELOPE VALLEY	5600251-103	P64375W	120	2,130	Well	Wasatch Fm
	ANTELOPE VALLEY	5600251-104	P102153W		10,614	Well	Wasatch Fm
	ARROWHEAD LODGE	5600480-101	P819AW		26	Well	
	ARROWHEAD LODGE	5600480-102	P819BW		26	Well	
	BALD MOUNTAIN TRAILER COURT	5600258-101	P23207W		200	Well	Wasatch Fm
	BALD MOUNTAIN TRAILER COURT	5600258-102	P99232W	18	240	Well	Wasatch Fm
	BALD MOUNTAIN TRAILER COURT	5600258-103	P33490W		200	Well	Wasatch Fm
	BALD MOUNTAIN TRAILER COURT	5600258-104	P64950W	7	180	Well	Wasatch Fm
	BEAR LODGE	5600479-101	P525W	25	74	Well	Plutonic Rock
	BEAR LODGE	5600479-102	P111458W	10	80	Well	Plutonic Rock
	BELLE FOURCHE P.L. DONKEY CRK	5601156-101			439	Well	Fort Union Fm
	BELLE FOURCHE P.L. DONKEY CRK	5601156-102			439	Well	Fort Union Fm
	BIGHORN MOUNTAIN CAMPGROUND	5600229-101			136	Well	Wasatch Fm
	BIGHORN NF - SIBLEY LAKE CG	5680231-101	P61644		125	Well	Plutonic Rocks
	BIGHORN NF BURGESS JCT VISITOR CNTR	5680232-101	P86363W	0	285	Well	Plutonic Rocks
	BIGHORN NF TIE HACK CG	5680184-101	P107962W		90	Well	Oldest Gneiss Complex
	BIGHORN NF-BURGESS RANGER STATION	5680244-101	P105302W		98	Well	Plutonic Rock
	BIRD DRIVE WATER SYSTEM	5600122-101	P2599W		1,210	Well	Fort Union
	BLACK HILLS NF-COOK LAKE CG	5680010-101	P74466W	10	65	Well	Sundance Fm

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Unknown (cont.)							
	BLACK HILLS NF-COOK LAKE CG	5680010-103	P74468W	5	260	Well	Sundance Fm
	BLM-MIDDLE FORK POWDER RIV CG	5680241-101	P100937W		45	Well	Alluvium
	BLM-MOSIER GULCH PICNIC AREA	5680234-101	P105982W		93	Well	Wasatch Fm, Moncrief member
	CAMPBELL COUNTY AIRPORT	5601023-101	P63913W	125	1,130	Well	
	CEDAR HILLS WATER ASSOCIATION	5600780-101	P45140W		640	Well	Ft. Union Fm. Tongue river and Lebo members
	CEDAR HILLS WATER ASSOCIATION	5600780-102	P45318W		1,365	Well	Ft. Union Fm. Tongue river and Lebo members
	CRESTVIEW ESTATES SUBDIVISION	5600853-101	P56901W		1,550	Well	Wasatch Fm
	DEVIL’S TOWER KOA-CAMPSTOOL ET	5600370-101	P82103W	50	1,375	Well	Madison Limestone
	DEVIL’S TOWER NAT’L MONUMENT	5680114-101	P1923W		1,341	Well	
	EATON’S DUDE RANCH	5600929-101	P134657W		1,740	Well	Madison Limestone
	EIGHT MILE SUBDIVISION	5600829-101	P88702W		1,466	Well	Wasatch Fm
	FORCE ROAD JOINT POWERS BOARD	5600148-101	P29916W		1,150	Well	Wasatch Fm
	FORCE ROAD JOINT POWERS BOARD	5600148-102	P56602W		1,520	Well	Wasatch Fm
	FORT PHIL KEARNEY ST HIST SITE	5600672-101	P14634W	5	88	Well	Wasatch
	FOUR J SCHOOL CAMPBELL SCH DIS	5601056-101	P70087W		750	Well	
	FREEDOM HILLS SUBDIVISION	5600789-101	P85154W		1,600	Well	Ft. Union Fm
	FREEDOM HILLS SUBDIVISION	5600789-102	P85155W		1,500	Well	Ft. Union Fm
	INDIAN CAMPGROUND	5601360-101	P1298W		15	Well	terrace deposits
	INTERSTATE INDUSTRIAL PARK	5600909-101	P33465W	50		Well	
	JACOBS RANCH MINE	5600924-101				Well	
	KEYHOLE RESORT/MARINA	5600373-101	P27054W	20	120	Well	
	KEYHOLE RESORT/MOTEL	5601249-101	P15574W		150	Well	
	KEYHOLE ST PARK COTTONWOOD	5600652-101	P144710W	20	284	Well	Ft. Union
	KEYHOLE ST PARK PAT’S POINT	5680180-101	P84789W		140	Well	Falls River SS
	KEYHOLE ST PARK PRONGHORN	5600651-101	P28556W	25	150	Well	Falls River Sandstone

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Unknown (cont.)							
	KOA BIGHORN MOUNTAIN	5600242-101	P69061W		380	Well	Fort Union Fm
	KOA BIGHORN MOUNTAIN	5600242-102			165	Well	Fort Union Fm
	KOA BIGHORN MOUNTAIN	5600242-103			165	Well	Fort Union Fm
	LAK RANCH	5601447-101	P75560W	100	4,190	Well	Madison Limestone
	LANCE CREEK WATER DISTRICT	5600109-101	P273W			Well	
	LANCE CREEK WATER DISTRICT	5600109-102	P272W			Well	
	MC GEE MOBILE HOME PARK	5601449-101	P27239W		275	Well	Wasatch Fm
	MEANS IMP. & SERVICE DIST.	5600760-101	P131367W		1,075	Well	Wasatch Fm
	MEANS IMP. & SERVICE DIST.	5600760-102	P131366W		1,456	Well	Wasatch Fm
	NICKELSON FARMS WATER COMPANY	5600619-101	P37957W	100	1,300	Well	Fort Union Fm
	NICKELSON FARMS WATER COMPANY	5600619-102	P52304W	100	1,488	Well	Fort Union Fm
	NORTH VIEW MOBILE HOME COURT	5600121-101	P45223W	25	491	Well	Wasatch Fm
	NORTHERN WY COMMUNITY COLLEGE	5601159-101	P84857W		1,166	Well	
	OSAGE WATER DISTRICT	5600038-101	P143G	200	3,000	Well	Madison Limestone
	OSAGE WATER DISTRICT	5600038-102	P50143W	25	3,101	Well	Madison Limestone
	POWDER RIVER CO-RAWHIDE MINE	5600815-101	P28705W	160	1,420	Well	
	POWDER RVR COAL-CABALLO MINE	5600328-101	P30008W	120	1,605	Well	Ft. Union Fm
	POWDER RVR COAL-CABALLO MINE	5600328-102	P84539W		1,400	Well	Ft. Union Fm
	PRAIRIE VIEW CAMPGROUND	5601070-101	P43048W		100	Well	Arikaree Fm
	RAG COAL WEST INC/RAWHIDE SCHOOL	5600123-101	P34920W	100		Well	
	RECLUSE SCHOOL CAMPBELL SCH DS	5601057-101	P40511W	15	1,230	Well	
	SAND CREEK TRADING POST	5600300-101	P59654W	4	39	Well	Alluvium
	SLEEPY HOLLOW SUBDIVISION	5600764-101	P98210W		2,410	Well	Wasatch Fm
	SLEEPY HOLLOW SUBDIVISION	5600764-102	P69561W		1,164	Well	Wasatch Fm
	SLEEPY HOLLOW SUBDIVISION	5600764-103	P69562W		1,479	Well	Wasatch Fm
	SLEEPY HOLLOW SUBDIVISION	5600764-104	P81859W		1,967	Well	Wasatch Fm

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Unknown (cont.)							
	SOUTHFORK ESTATES	5600832-101	P57603W		1,600	Well	Wasatch Fm
	STONE GATE ESTATES	5601329-101	P87209W	25	1,706	Well	Wasatch Fm
	STONE GATE ESTATES	5601329-102	P95375W	80	1,620	Well	Wasatch Fm
	STORY ELEMENTARY SCHOOL	5600578-101	P54850W		90	Well	
	TRITON COAL CO-BUCKSKIN MINE	5600818-101	P46018W		1,362	Well	Ft. Union Fm
	TRITON COAL CO-BUCKSKIN MINE	5600818-102	P110771W		1,510	Well	Ft. Union Fm
	U.S. AIR FORCE DET 21, ECRG	5601117-101			647	Well	Greenhorn Fm
	UCROSS GUEST RANCH	5601149-101	P102121W		795	Well	
	UNION PACIFIC RAILROAD	5600978-101	P79678W	110	1,471	Well	
	UNION PACIFIC RAILROAD	5600978-102	P70871W	40	1,473	Well	
	VISTA WEST SUBDIVISION	5600246-101	P91988W		400	Well	Intrusive/Extrusive igneous rocks w/ Mississippian through Cambrian masses
	VISTA WEST SUBDIVISION	5600246-102	P91989W		1,140	Well	Intrusive/Extrusive igneous rocks w/ Mississippian through Cambrian masses
	WAGON BOX INN	5601103-101	P62530W	25	60	Well	Alluvium/Colluvium
	WAGON BOX INN	5601103-102	P80128W			Well	Alluvium/Colluvium
	WESTERN FUELS-WYOMING INC.	5601214-101	P69886W		1,814	Well	Ft. Union Fm
	WESTON COUNTY MALLO CAMP	5600515-101	P1516W		18	Well	Alluvium
	WESTRIDGE WATER USERS ASSOC.	5600146-101	P24603W	80	1,360	Well	Wasatch Fm
	WESTRIDGE WATER USERS ASSOC.	5600146-102	P14224W	25	1,186	Well	Wasatch Fm
	WINLAND INDUSTRIAL PARK	5601410-101	P61523W		1,090	Well	Wasatch Fm
	WRANGLER ESTATES	5601474-101	P132906W		1,620	Well	Fort Union Fm
	WY TRANS DEPT - WALTMAN RA	5600964-101	P70877W	15	142	Well	Wind River Fm
	WY TRANS DEPT MOORCROFT RA	5600730-101	P19065W	25	300	Well	
	WY TRANS DEPT POWDER RIVER RA	5600949-101	P76205W	25	1,002	Well	
		5600487-101	P50731W	25	21	Well	

Table 8-12. continued

Municipality	Well name	Public water system ID	WSEO permit no.	Yield (gpm)	Well depth (ft)	Source type	Producing unit
Unknown (cont.)							
		5600487-102	P50730W	17	25	Well	
		5600487-103	P5495W	20	32	Well	
		5600545-101	P15230W	15	100	Well	
		5601050-101	P71452W	60	1,494	Well	
		5601192-101	P60219W	20	921	Well	Ft. Union Fm
		5680179-101	P28560W	25	180	Well	Falls River SS

2012 Wind/Bighorn River Basin Water Plan) have treated produced water withdrawals as industrial groundwater use, while others (e.g., the 2006 Platte River Basin Water Plan) have included only water used for production and refining operations in estimates of industrial use. The information in chapter 10 on currently produced water associated with energy operations was obtained from the WOGCC (2017), the U.S. Geological Survey USGS (Maupin and others; Lovelace, 2009), and the U.S. Energy Information Administration (2018).

Figures 5-4 through 5-6 show the extent of energy development as it relates to water resources in the NERB. Figure 5-4 shows conventional oil and gas infrastructure, figure 5-5 provides the locations of Class II (petroleum-produced water) and Class V (CBM-produced water) injection wells, and fig. 5-6 maps Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls and WDEQ groundwater pollution control facilities.

Chapter 10 examines energy production and groundwater. Table 10-1 lists annual production levels of oil, gas, coal, and produced-water during 2003–2016.

Effluent waters from various facilities of suitable quality can be put to beneficial use (e.g., stock watering, agriculture, drilling, and industrial dust suppression). Otherwise, effluent water is primarily discharged to the surface under the regulation of WDEQ Wyoming Pollutant Discharge Elimination System (WYPDES) permits. WDEQ data indicate that most WYPDES permits shown in figure 5-6, particularly in the Powder River, Belle Fourche, Tongue, and Cheyenne River basins, were issued in association with coalbed methane production. Estimates of historical volumes of CBM co-produced water discharged in the NERB can be obtained from the WOGCC website, http://pipeline.wyo.gov/crms.cfm.

Produced water volumes that are discharged to the surface or put to other uses are generally considered to be partially consumptive and, in a few cases, wholly consumptive. Produced (effluent) water management typically involves some consumptive losses to evapotranspiration. On the other hand, injecting produced water into hydrogeologic units at depths where there is minimal chance of future withdrawal effectively removes it from the water budget of the basin and is wholly consumptive. The water balance developed within this study adds discharged effluent water volumes to precipitation. Once discharged, effluent waters are consumed by evapotranspiration, add to surface water outflows, and recharge shallow aquifers.

8.6.3.8.2 Groundwater use for non-energy minerals development

Groundwater withdrawn for non-energy mineral development in the NERB is primarily used for the production of sand, gravel, limestone, bentonite, and scoria. Figure 5-8 shows the locations of groundwater permits for non-energy minerals, coal, and uranium mines in the NERB.

Mining permits are shown on the WDEQ Land Quality Division website: http://deq.wyoming.gov/lqd/.

8.6.3.9 Monitoring wells

Tables 8-6 through 8-8 list 7,930 SEO monitoring well permits in Wyoming, 109 monitoring wells in Montana, and 13 in South Dakota. Monitoring wells are typically used to track the levels and quality of groundwater associated with a contaminated site or a potentially contaminated site (e.g., an underground fuel storage tank) or to monitor for groundwater impacts from various activities (e.g., mining or waste management). When used for monitoring alone, these wells have no permitted yield; however, there may be a permitted yield for other, secondary uses. The SEO stopped requiring permits for monitoring wells of 4 in or less in diameter in 2004; therefore, the data for these permits are incomplete.

Figure 8-6 shows the distribution of likely drilled SEO monitoring well permits in the NERB. Most monitoring wells are located along Wyoming State Highway 59 in association with operating coalmines. The depth versus yield tables on figure 8-6 show that most permits are issued for depths less than 500 ft. This suggests that shallow water table aquifers susceptible to contamination are the most frequent target of groundwater monitoring programs in the NERB. Although recorded depths are available for most monitoring wells in the database, only 66 well permits include recorded yield data. More than 800 monitoring wells were permitted after 2002; however, even this high number is understated because of the 2004 SEO policy change that removed the permit requirement for monitoring wells under 4 in in diameter.

8.6.3.10 Permits for other and miscellaneous uses

Table 8-6 indicates that the SEO has issued 3,387 permits for “other” uses and 4,813 permits for “multi-use” wells. Multi-use permits list more than one use; for example, a permit that shows both “domestic” and “stock” use is a multi-use permit. Tables 8-7 and 8-8 list permits for “other” wells and “multi-use” permits issued by Montana and South Dakota, respectively. There are no permits recorded for either type in Nebraska (table 8-9).

Some "multi-use" permits are for test wells used to determine aquifer hydraulic characteristics. Information on specific miscellaneous-use and test wells may be found in some permit SEO applications available online and in the WWDC water projects listed in appendix B.

Figure 8-7 shows that miscellaneous-use and other-use wells are located throughout the NERB. The depth versus yield tables in figure 8-7 show that most groundwater permits have been issued for depths up to 99 ft and for yields of 1 to 499 gpm for both total permits and permits issued since 2002. About 30 percent of these permits do not list a recorded depth.

8.6.3.11 Hydrothermal use

The NERB has no potential for high-grade geothermal energy development. However, Buelow and others (1986) identified three areas in the NERB with limited potential for hydrothermal development: the Salt Creek-Meadow Creek area north of Casper, along Lightning and Lance creeks in the Cheyenne River Basin, and on the southwestern flanks of the Black Hills near Newcastle. A WSGS inventory of thermal springs in Wyoming (Breckenridge and Hinckley, 1978) did not identify any hydrothermal springs in the NERB.

The SEO database lists hydrothermal development as a sub-category in individual permit applications for some miscellaneous-use wells. Determination of the number of wells and springs permitted for hydrothermal use was beyond the scope of this study.

8.7 GROUNDWATER INTERFERENCE/ INTERCONNECTION WITH SURFACE WATER

The potential for interference between wells and well fields located within areas of interconnected surface and groundwater that exhibit historically high levels of drawdown must be considered when assessing the historic, current, and future use of groundwater in the NERB. The use of groundwater resources is not addressed in the Belle Fourche and Yellowstone compacts but is mentioned in the Upper Niobrara Compact (app. D).

8.7.1 Interference between wells

As a well withdraws water from an unconfined aquifer, it depresses the groundwater level around the well casing in a generally radial configuration, called a "cone of depression." In areas where several actively pumping wells are sited in close proximity to each other, their respective cones of depression may overlap and "well interference" may result. If well interference becomes excessive, aquifer water levels may drop below the depth of some wells, causing conflicts between users. In Wyoming, the SEO may address cases of excessive well interference by recommending the formation of a groundwater control area wherein groundwater uses are actively managed by a groundwater control area advisory board. According to Wyoming State Statute WSS 41-3-912, a "control area" can be designated by the Board of Control on the recommendation of the State Engineer for any of the following reasons:

- The use of underground water is approaching a use equal to the current recharge rate
- Groundwater levels are declining or have declined extensively.
- Conflicts between users are occurring or 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.

Currently, there are no designated control areas in the NERB. Additional information about groundwater control areas can be found online: https://sites.google.com/a/wyo.gov/seo/ground-water/groundwater-control-areas-advisory-boards.

8.7.2 Interconnection between groundwater and surface water

Surface flows are subject to strict water rights, and conflicts occur where groundwater extraction affects surface flow. Although the Wyoming Constitution establishes that all surface water and groundwater within Wyoming's borders is owned by the state, the right to put surface water and groundwater to beneficial use is permitted as water rights by the Wyoming SEO and adjudicated by the Wyoming Board of Control. Surface water resources are subject to interstate agreements that limit how much streamflow can be depleted before leaving the state. Furthermore, conflicts among users within the state or across state lines can occur where groundwater extraction may affect surface flows. Although interconnection between groundwater and surface water is not currently a significant water rights issue in the NERB, it could become a point of contention in the future as the basin's population grows.

Appendix D contains copies of the Belle Fourche, Yellowstone, and Upper Niobrara compacts (SEO, 2017). The Interstate Streams Division of the SEO administers the provisions of compacts that fall under the authority of the State of Wyoming.

Chapter 9

Looking to the future

Karl G. Taboga

The purpose of this chapter is to discuss future water use opportunities in the NERB. This issue was examined in detail in previous NERB water plans (HKM and others, 2002a, b) and the Wyoming Framework Water Plan (WWC Engineering and others, 2007). This study provides the most current information available about the future focus and direction of NERB groundwater development projects.

The technical concepts and geology previously discussed in this study provide the background required to understand the practical considerations that shape the conceptualization and design for a successful completion of a water resource development project. Chapter 5 opened with the definition of several hydrogeologic concepts crucial to understanding basic groundwater science. Section 5.1.3 introduced the dynamics of groundwater recharge, discharge, and flow, and summarized the hydrogeologic characteristics of the complex geologic settings in the NERB. Future groundwater development in the NERB is physically limited by hydrogeology. Specific groundwater development projects are discussed in section 9.1, and recommendations for future updates of this groundwater determination technical memoranda are presented in section 9.2.

Additional supporting information for the project assessments contained in this chapter can be found in previous chapters of this study:

- Basin hydrogeology is discussed at length in chapters 5 through 7 and illustrated in plates 4, 5, and 6.
- Groundwater chemical characteristics are summarized in chapter 7 and appendices E and F.
- Recent and historic development patterns specified by beneficial use are examined in chapter 8. These patterns were provided by the Wyoming State Engineer's Office.
- Studies published by the USGS (chap. 7) and Wyoming Water Development Office (WWDO) (appendix B) examine the development potential of specific aquifers.
- The 2002 Water Plan for the NERB (HKM and others, 2002), the 2017 Water Plan (RESPEC, 2019) and associated technical memoranda, as well as the 2007 State Water Plan (WWC Engineering and others, 2007), identify potential groundwater development projects considered prior to the completion dates of those studies. Many of the opportunities examined in those publications may be under current development or will become more viable in the future as financial factors and technological improvements allow.
- The Water Resources Data System (WRDS) library, specifically the WWDC Projects and Studies webpage (http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html), contains hundreds of water development reports for projects completed in the last 40 years for localities throughout Wyoming.

This chapter discusses development projects designed with the primary objective of producing potable groundwater. Projects that may produce groundwater as a value-added byproduct of other activities, such as oil and gas production or in-situ mineral extraction, are not considered.

9.1 FACTORS THAT AFFECT GROUNDWATER DEVELOPMENT

- Water availability—A groundwater resource must be legally, economically, and physically available. In the semi-arid west, the significance of the last two factors cannot be overstated. Large sources of good quality groundwater exist in most Wyoming river basins, but in many cases they are located at such distances from population centers that development is uneconomical. In the NERB, there are few legal constraints on groundwater development and availability is controlled primarily by hydrogeology. Fortunately, most of the basin's communities are located in proximity to productive aquifers.
- Funding—Groundwater development projects are expensive and most Wyoming municipalities lack the funds required to plan, carry out, and complete development programs. Therefore, funding for some projects has to be obtained from other governmental agencies. The primary water development funding agencies in Wyoming are the WWDC, DEQ, and the U.S. Department of Agriculture.
- Stakeholder involvement—The successful completion of any groundwater project requires the involvement of stakeholders who have interests in the development or preservation of a particular water resource. Stakeholders include: municipal, state, and federal regulatory agencies; current and future water users; landowners; business representatives; attorneys; scientists, engineers; environmental groups; sportsmen; and holders of competing water rights. Stakeholder support

for a water development project depends on the nature, benefits, costs, and perceived impacts of the particular project. The project will likely incur substantial cost increases and time delays if legal challenges are filed by stakeholders opposed to development.

- Interstate compacts—In the NERB, interstate compacts regulate surface water uses on the Belle Fourche (1943), Yellowstone (1950), and Upper Niobrara (1962) rivers. However, only the Upper Niobrara River Compact of 1962 recognizes the interconnection between groundwater and surface water resources and lays the foundation for groundwater apportionment in the future. The Interstate Streams Division of the SEO administers all interstate stream compacts for the State of Wyoming (https://sites.google.com/a/wyo.gov/seo/interstate-streams). Currently, there is no interstate regulation of groundwater use in the basin.

- Water quality—Groundwater produced must meet the water quality requirements of the intended use(s). State and federal laws mandate water quality requirements for certain beneficial uses. These benchmarks may or may not be used as reference measures for water acquired by other means. For example, the National Primary Drinking Water Regulations (table 5-1), established by the Environmental Protection Agency (EPA) under provisions of the Safe Drinking Water Act, are legally enforceable standards for public water systems (PWS), but do not regulate water quality in private groundwater wells that serve fewer than 25 people. Still, water quality in private wells is frequently evaluated in comparison to the Maximum Contaminant Levels (MCL) contained in the EPA regulations.

- Environmental regulation—Water development projects in Wyoming are subject to regulation under the provisions of state and federal environmental laws including:
    - Wyoming Environmental Quality Act—the principal state environmental law that created the Wyoming Department of Environmental Quality, repealed the state's existing environmental laws (in 1973) and replaced them with the provisions of the new act.
    - Endangered Species Act—a federal environmental law designed to protect imperiled plant and animal species. The ESA is administered under the Endangered Species Program of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration (NOAA).
    - National Environmental Policy Act (NEPA)—the main federal law that established national environmental policy. It requires federal agencies in the executive branch to write Environmental Impact Statements (EIS) and Environmental Assessments (EA) that examine anticipated impacts to the environment resulting from proposed federal agency actions.
    - Clean Water Act—the principal federal law that governs pollution in the nation's surface waters. The CWA does not regulate groundwater pollution directly. The Water Quality Division of DEQ regulates the discharge of pollutants to surface waters under the CWA.
    - Safe Drinking Water Act (SDWA)—the primary federal law that ensures safe drinking water supplies for the public. The SDWA covers public water supplies but does not apply to private wells that serve less than 25 people. The EPA administers and enforces provisions of the SDWA.

9.1.1 Groundwater development projects in the NERB

Appendix B contains a chronological summary of groundwater development related projects sponsored by the WWDC in the NERB since 1973. Information contained in many of these studies was used to detail the physical and chemical characteristics of the basin's hydrogeologic units in chapter 7. Appendix B summarizes the following groundwater development information for WWDC projects in the NERB:

- References to the study(s)—full citations are included
- Location—name of the community, county, rural area, irrigation district, well site, etc.
- Aquifers involved in the study
- Descriptions of development project(s) and aquifer development potential
- Summary of results
- Current project status

9.1.2 Future water use opportunities

Technical memoranda (Memorandum "S") of the 2002 Powder/Tongue River Basin Water Plan (HKM, 2002a) and the Northeast Wyoming River Basin (HKM, 2002b) provide detailed discussions of future water use opportunities that could expand water supplies to meet current and future demands. These water use opportunities were initially developed by the respective Basin Advisory Groups (BAGs) for these rivers basins in 2002 and can be reviewed online at: http://waterplan.state.wy.us/basins/basins.html.

The BAGs evaluated four categories of promising water development projects on the basis of availability, financial feasibility, public acceptance, number of beneficiaries, legal constraints, and environmental benefits. These four categories are:

- Category 1: Rehabilitation projects that preserve existing uses
- Category 2: Projects that rectify existing shortages
- Category 3: Projects that meet projected future demands
- Category 4: Projects that enhance uses in other Wyoming basins

Most of the opportunities discussed in Technical Memoranda "S" for both the Powder/Tongue and the Northeast Wyoming river basins (HKM and others, 2002a, b) involve Category 2 and 3 surface water projects, particularly improvements to existing reservoirs or construction of new reservoirs. Groundwater projects include:

- Generally increasing groundwater development in both river basins
- Exploring the feasibility of CBM aquifer storage and retrieval
- Studying the feasibility of trans-basin groundwater diversions to Gillette

This chapter discusses potential new groundwater development in the NERB by examining the basin's major aquifer systems (sec. 9.1.3) and overviews of recent WWDC groundwater development projects (sec. 9.1.4).

9.1.3 Groundwater development potential by aquifer system

Currently, the Belle Fourche, Upper Niobrara and Yellowstone interstate river compacts (app. D) do not restrict groundwater development in the NERB. Thus, future groundwater development projects will be designed and completed based on the location and magnitude of future water demands, groundwater availability and quality, funding, stakeholder involvement, and environmental regulations. Table 9-1 summarizes further groundwater development potential in the basin's main hydrogeologic units.

Virtually all aquifers and some confining units in the NERB have some physical potential for development (pl. 2 and table 9-1), depending on the needed quantity, the quality required by the specified beneficial use(s), and technical limitations. The Tertiary Wasatch/Fort Union aquifer system remains available for future groundwater development. Additionally, Mesozoic and Late Paleozoic bedrock aquifers are underutilized and may be prime targets for future development, especially within or in close proximity to exposures where recharge is actively occurring, where residence times are low, and where water quality is good. Although well yields could be expected to range from 10 to 500 gpm in these aquifers, water quality and susceptibility to surface sources of contamination (e.g. irrigation return flows and leachates from septic systems) should be considered in evaluating development prospects.

9.1.4 Groundwater development potential—an economic perspective

Table 9-1 indicates that large sources of good quality groundwater can be found in the NERB. However, these resources may be located at such distances from population centers that development is uneconomical. The cost of constructing the pipelines necessary to convey water to an urban area may far exceed the cost of installing municipal wells in a productive aquifer. For example, projected costs for the Gillette Regional Water System (HDR and others, 2009) were estimated at \$19.36 million for the installation of 11 Madison aquifer wells and \$69.08 million for the construction of the 41-mile long transmission pipelines.

Given the complexities encountered in determining when and where groundwater development is economically feasible, examinations of recent WWDO groundwater projects and existing public water systems in the NERB provide the most realistic evaluations of future groundwater development potential. The consultant reports associated with WWDO projects (app. B) carefully consider how the various factors discussed in section 9.1 will impact the economic development of groundwater resources in each project area. The following section examines the aquifers most frequently targeted for municipal/domestic uses.

Table 9-1. Generalized groundwater development potential for major regional aquifer systems in the NERB (modified from WWC Engineering and others, 2007; chap. 7, this report).

Age	System	Outcrop location	Well yields	Major aquifers	General potential for new development
Quaternary	Alluvial	Scattered throughout NERB	Small to large	Unconsolidated deposits	Fair to good. Water quality may be poor
	Non-alluvial	Scattered throughout NERB	Small to moderate	Primarily unconsolidated terrace deposits but locally can include glacial deposits	Poor to fair. Most deposits located above stream channels exc. W Sheridan County
	Volcanic Rocks	Black Hills	Small	Undifferentiated volcanic deposits	Poor to fair—deposits of limited extent located distant from population centers
Tertiary	Late	Niobrara R. basin	Small to large	Arikaree	Good to very good
	Early	Tongue, Powder, Little Powder, Upper Belle Fourche, Upper Cheyenne	Small to large	Lower Tertiary aquifer system (Wasatch and Fort Union Formations) including coal aquifers	Good to very good—varying water quality
Mesozoic	Upper Cretaceous	Widespread along perimeter of PRSB	Small to moderate	Upper Cretaceous aquifer system (Lance Formation and Fox Hills Sandstone), Locally Mesaverde, and Frontier formations	Fair to good—varying water quality
	Lower Cretaceous	Widespread along perimeter of PRSB; flanks of Black Hills and Bighorn Mts.	Small to moderate	Muddy, Newcastle, Cloverly, Inyan Kara	Poor to good—varying water quality
	Jurassic/Triassic/ Permian	Outcrops flanks of Black Hills	Small	Sundance, Spearfish, Minnekahta	Fair in some local areas—poor to good water quality
Paleozoic	Upper	Widespread along perimeter of PRSB; flanks of Black Hills and Bighorn Mts.	Small to very large	Madison/Pahasapa, Tensleep/ Minnelusa	Good to very good—poor to good water quality
	Lower	Widespread along perimeter of PRSB; flanks of Black Hills and Bighorn Mts.	Small to large	Flathead, Bighorn, Deadwood	Fair to good—some marginal water quality

Summary information for WWDC funded water development projects is listed in appendix B under the name of the community, watershed, or locale served by the project. Projects for subdivisions may be found under the subdivision name or, in some cases, the name of the neighboring municipality. Complete project reports can be accessed by the public at: http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html.

9.1.4.1 Economic development of potable groundwater

Economic groundwater development of domestic and public supplies in the NERB has been largely determined by geographic location (table 9-2). Generally, communities near or along the eastern margin of the Powder River Structural Basin have targeted the Madison aquifer, its equivalents, and associated Paleozoic formations. Dayton and Kaycee, two towns on the western margin of the PRSB, also obtain their water from the Madison aquifer where it dips steeply along the eastern flank of the Bighorn Mountains. Most public water systems for communities in the interior PRB utilize groundwater from the Wasatch/Fort Union or Lance/Fox Hills Aquifer systems. The Inyan Kara aquifer, the stratigraphic equivalent of the more widely occurring and named Cloverly Formation, provides municipal water to Lance Creek, a Census Designated Place in western Niobrara County. Lusk and Manville in southern Niobrara County obtain their municipal water, in part, from wells recently installed in the Tertiary Arikaree aquifer.

The Madison aquifer and its equivalent, the Pahasapa Limestone, and the Tensleep Limestone and its Minnelusa equivalent are the most frequently accessed units in the Paleozoic aquifers. WWDC development projects associated with the Paleozoic aquifers include exploration wells in the communities of Aladdin, Dayton, Hulett, Kaycee, Moorcroft, the Newcastle area, Pine Haven, Sundance, and Upton. Several WWDC development projects evaluate water system improvements for communities served by the Gillette Regional Water Supply System which is partially supplied from the Madison aquifer. Projected or actual community well yields in the Paleozoic units range from 25 to 1500 gpm. Water quality is usually good to excellent, and generally meets EPA standards. Exceedances for sulfate, TDS, and iron were observed in water samples from some community wells. Access to the Paleozoic aquifers in some locations requires that municipal wells be drilled to depths greater than 3,400 ft.

The WWDC has funded groundwater exploration projects in the Tertiary aquifer system for Antelope Valley-Crestview, Cook Road, Gillette, Pine Butte, Sleepy Hollow, and Wright. WWDC also funded a hydraulic evaluation of existing wells in Clearmont. Actual municipal well yields in the Tertiary aquifer system range from 5 to 500 gpm. Groundwater quality generally meets the EPA drinking water standards. The most commonly observed exceedances include fluoride, radium, iron, and TDS. Generally, the best quality water is found in the lenticular sandstones of the Tongue River Member of the Fort Union Formation (Soda Butte Services, Inc. and others, 1994; Wester-Wetstein & Assoc., Inc., 2004). Groundwater from the Tullock Member is generally higher in fluoride, sodium, and TDS (Wester-Wetstein & Assoc., Inc., 2004). Total depths of Tertiary system municipal wells may be as high as 3,000 ft.

In the Upper Niobrara Basin communities of Lusk and Manville, groundwater is obtained from the Arikaree Formation of the High Plains aquifer system. WWDC exploration wells in the Arikaree yield up to 400 gpm and are completed at depths of less than 500 ft. Groundwater from the Lusk #9 Test Well did not meet EPA standards for uranium and gross alpha particle levels.

9.1.5 Current WWDO, USGS, and SEO projects

In addition to the previous studies summarized in appendix B, the WWDO is updating the previous Powder/Tongue and Northeast River Basin water plans (HKM Engineering and others, 2002a, b) and constructing a hydrological model for surface flows in the basins (RESPEC and others, 2019 a, b). WWDO is also conducting groundwater projects in Buffalo, Lusk, and Clearmont (http://wwdc.state.wy.us/planning_program/all_projects.html) Additionally, the USGS continues to collect real-time streamflow data and periodic water quality at 21 USGS stream gaging stations located in the basins (http://waterdata.usgs.gov/wy/nwis/current/?type=flow).

9.1.6 Groundwater interference and interconnection with surface water

Other factors that must be considered for new groundwater projects are the potential for interference between wells or well fields completed in the same aquifer, excessive drawdowns in over-utilized aquifers, and interconnections between groundwater and surface water. Wells alone do not necessarily present significant problems to a public water system depending on several factors, including the physical and hydrogeologic properties of the target aquifer, construction of the production wells, and the timing and rate(s) of well production. In aquifers possessing high degrees of secondary (fracture) permeability, well interference may occur over the scale of several miles. In many cases, municipal water supply personnel are aware of well interference effects in their facilities, and effectively manage them by adjusting well pumping times and rates, or by periodically switching to other sources of municipal water.

Excessive drawdown, or groundwater depletion, in over-utilized aquifers has become a national concern (Stanton and others 2011; Konikow, 2013). It is a concern in parts of the Powder River Structural Basin where coalbed natural gas (CBNG) production was extensive. Groundwater declines of more than 100 ft have been documented in some PRB coal seam aquifers (Taboga and others, 2015) and in adjacent sandstone strata (Taboga and others, 2017) during CBNG production. Further monitoring is needed to quantify groundwater level responses to subsequent declines in CBNG production in the affected aquifers. Further monitoring may also reveal how these changes may impact adjacent aquifers that provide potable water to basinward communities (WSEO, 1995; Weston Engineering, 2008).

Large declines in hydraulic head from over-pumping can reduce aquifer water levels to the point where groundwater discharges to surface water bodies are reduced, thereby diminishing streamflow volumes (Barlow and Leake, 2012). In extreme cases, groundwater levels may decline below the elevation of the streambed, causing streamflows to recharge the aquifer. This effect, called pumping-induced recharge, may dry up spring flows or turn gaining streams into losing streams (Winter and others, 1998; Barlow and Leake, 2012).

9.2 RECOMMENDATIONS FOR FUTURE UPDATES

The quality of the Wyoming State River Basin water plans is limited by the availability of data and the institutional resources used to develop the compiled information into a readily accessible and useful format for stakeholders. While some information (e.g., hydrogeology studies, SEO groundwater permits, data from the DEQ and other agencies) is generally available for all basins, other information (e.g. regional groundwater modeling) does not exist. The quantity, accuracy, and completeness of available groundwater information vary between the major drainage basins of Wyoming.

The purpose(s) of updating an available groundwater determination memorandum can be to include new information, to include older information not initially provided, or to utilize continuously improving technology to maximize the value of the information presented. While information in some areas will grow slowly (e.g. mapping of geologic and hydrogeologic units), other information (e.g., SEO and other agency data) requires regular updates to maintain its utility.

9.2.1 Data challenges

Computing capabilities will continually improve but will always be limited by the availability and reliability of the input data. The quality of a compilation study such as this relies on the quality of the available data. The development of a comprehensive statewide database for water quality and aquifer physical characteristics would greatly assist Wyoming water professionals to manage and protect the state's valuable water resources.

Currently, hydrogeologic and hydrogeochemical data exist that could be integrated into a more comprehensive and evolving groundwater database for Wyoming. For example, DEQ collects copious amounts of groundwater data for site-specific investigations of contaminated sites, for issuing industrial permits (e.g. mining, underground injection control, waste and wastewater management), and for monitoring for potential impacts. The SEO collects groundwater information from selected wells. The USGS, WOGCC, BLM, EPA, counties, municipalities, other agencies, and private entities all collect hydrologic information for a variety of activities and purposes. However, coordination between the various entities collecting groundwater information is generally lacking, and clearly there is abundant relevant information that was not and is not accessible for this study and groundwater determinations in other basins. While the quality of some of this information may not be consistent with the standards described in chapter 7, those data could be qualified. Some data (e.g., on contaminated samples), however, would not be representative of natural groundwater, and some water quality analyses (e.g., for contaminated sites and industrial site monitoring) would be for constituents not commonly used to characterize natural groundwater quality; nevertheless, a comprehensive database would be useful.

Ongoing revision and maintenance of a comprehensive groundwater information database where data are continually being generated by numerous entities would be a substantial project, requiring a continuing commitment of resources by federal, state, and local agencies, and is certainly easier described than done. As interest in groundwater resources increases, so will justification for such a program.

9.2.2 Current and future research efforts

This study is a compilation of previous investigations conducted primarily by state and federal agencies and consultants. Any significant advancements in the development of the conceptual model of the hydrogeology of the northeast river basins require further original research, most likely conducted by academic investigators, USGS water scientists, or by consultants employed by the WWDC, SEO, or Wyoming municipalities. The recent formation of the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) should prove to be particularly valuable to developing a better understanding of groundwater resources in NERB. Funded for a five-year period by the National Science Foundation, WyCEHG efforts are specifically targeted to advancing research in western hydrologic systems using advanced geophysics and remote sensing technologies. The stated goals of WyCEHG are:

- To improve understanding of mountain front hydrology by characterizing the processes that partition water into streams, soils, plants, rivers, and aquifers in several locations throughout the state
- To improve understanding of how disturbances affect water flux by studying effects on hydrological systems from climate change, bark beetle infestations, and energy extraction
- To improve integrated modeling of the fate and transport of water by creating integrated computer models that will provide the scientific knowledge and tools for improved prediction of hydrological processes
- To provide cutting edge resources and tools for educators and watershed managers in the state

Further information for WyCEHG can be accessed at: http://www.uwyo.edu/epscor/wycehg/.

The recharge calculations contained in section 6.2, went beyond summarizing existing information by using the data to estimate the groundwater resource. The recharge evaluation in this study could easily be updated and the results refined as new data is collected, with a relatively low-level commitment of resources. The estimation of recharge can be enhanced by numerical modeling in selected areas that include additional variables that affect infiltration and recharge (sec. 5.1.3).

Finally, there are several areas where additional geologic mapping would develop useful information for future water plan updates. More detailed geologic mapping would better define the hydrogeologic role of the basin's geology, further identify areas where groundwater and surface water may be interconnected, and determine areas where vertical recharge may be enhanced by fracture permeability.

Chapter 10

Energy development and groundwater

Karl G. Taboga

The NERB encompasses most of the Wyoming portion of the Powder River Basin Province (PRBP), one of the most prolific areas of fossil fuel production in the United States (Anna and others, 2009). The Powder River Basin's extensive deposits of coal as well as most of its oil and natural gas resources are located in the NERB. Moreover, during the period from 2002 to 2016, the Powder River Structural basin produced nearly 5.6 trillion mcf (thousand cubic feet, a standard measure of natural gas) of coalbed methane gas (CBM). In comparison, CBM production during the same period in the rest of Wyoming was a little more than 188 million mcf (WOGCC, 2017). Interactive online maps, available from the Wyoming Department of Environmental Quality (WDEQ) (http://deq.wyoming.gov/lqd/coal) and the Wyoming Oil and Gas Conservation Commission (WOGCC) (http://wogccms.state.wy.us/flexviewers/unitmap/), show the extent and location of active coal mines and oil and gas wells in the NERB, respectively. The WSGS provides an overview of energy resources in Wyoming structural basins at: http://www.wsgs.wyo.gov/energy/energy.

10.1 ENERGY PRODUCTION AND GROUNDWATER IMPACT

Energy resource development usually affects groundwater resources in some manner. Coal mines must be de-watered when mining extends into saturated geologic units. Groundwater must be pumped from saturated coal seams to extract coalbed methane. Oil and gas wells typically discharge co-produced groundwater present within the targeted hydrocarbon reservoir(s) during production; (see http://www.wsgs.wyo.gov/energy/oil-gas-resources for an explanation of how oil, gas, and water exist together within a petroleum reservoir). Groundwater recharge may be enhanced or decreased by surface disturbances related to development. The practices employed to manage co-produced waters can substantially alter surface water and groundwater volumes (Taboga and others, 2015; 2017) and hydrochemistry (Healy and others, 2011; Clark, 2012).

10.1.1 Energy production and co-produced groundwater

Table 10-1 and figure 10-1 illustrate hydrocarbon and groundwater production volumes in the NERB for 2002–2016. Annual water production volumes for traditional oil and gas (TOG), coalbed methane (CBM), and injection/disposal wells were obtained from operator-supplied data, as reported to the WOGCC (2018). Groundwater production volumes associated with coal mining were calculated by multiplying annual coal production (U.S. Energy Information Administration, 2018) by groundwater production rates per short ton of coal mined (Lovelace, 2009).

Groundwater produced from all forms of energy development (fig. 10-1) in the NERB has declined from a peak of more than 184,000 ac-ft in 2008 to about 90,000 ac-ft in 2016. The observed decline is due largely to a four-fold decrease (from 88,000 to 22,000 ac-ft) in CBM water production from 2008 to 2016. In comparison, the less variable groundwater volumes produced from coal mining and traditional oil and gas development have declined at relatively modest rates (fig. 10-**1**).

Injection and disposal wells pump water and other fluids into deep geologic units. Disposal wells are for disposing hydrocarbons, brines, or other fluids produced in conjunction with oil and gas production. Injection wells inject water, gases such as CO_2, or a combination of water and gases into petroleum reservoirs to achieve secondary recovery of oil and natural gas. Injection and disposal wells are regulated by the WOGCC as Class II underground injection control permits.

In most cases, injection and disposal wells pump fluids into deep geologic units where depth and water quality would prevent future withdrawal. Although disposal volumes have remained relatively constant at about 3,500 ac-ft/yr (table 10-1) between 2002 and 2016, annual injected water volumes (fig. 10-1) have been steadily declining since 2002.

10.1.2 Produced groundwater management

Managing co-produced groundwater is a critical environmental issue that must be addressed in any energy development project. In some cases, the costs and logistics of water management have hampered or halted project development. Produced water extraction and management were, and have remained, pivotal issues in the Powder River Basin during the accelerated development of surface coal mining (Bloyd and others, 1986) that began in the 1970s, and the more recent period (1999–present) of CBM development (Peterson and others, 2010; Bern and others, 2013).

The WDEQ and WOGCC are the principal regulators of produced water in Wyoming. However, developing a produced water management program frequently requires close coordination with other state and federal environmental agencies. Depending on the location of production and the management strategies proposed, developers may be required to comply with regulations and/or obtain permits from the Bureau of Land Management

(BLM), SEO, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency (EPA), U.S. Forest Service (USFS), and U.S. Fish and Wildlife Service (FWS).

The produced water management methods most commonly employed in the NERB include:

- Discharging produced water to receiving waters (streams, waterways) of the state, closed basins, playas, headwater reservoirs, and on-channel containment units. These projects require permits from the WDEQ Wyoming Pollutant Discharge Elimination System (WYPDES) Program.
- Using produced waters for other uses such as irrigation, livestock watering, wildlife watering, dust suppression on roadways, and some on-site industrial processing. These projects also require WYPDES permits, as the produced waters are likely to enter waters of the state.
- Storing produced water in off-channel pits or sending it to designated disposal and injection wells requires permits from the WOGCC (chaps. 4, secs. 1, 5, and 7 in http://wogcc.state.wy.us/wogcchelp/commission.html).

These water management methods are largely consumptive. Evapotranspiration consumes much of the produced water discharged to surface waterways and impoundments, as well as that used for agriculture and dust suppression. Injection and disposal wells pump produced water into deep geologic units, many of which are saline petroleum reservoirs.

10.1.3 Additional information

Further information about produced water management and its impacts can be found at the following websites:

- WDEQ WYPDES Program: http://deq.wyoming.gov/wqd/wypdes/
- WOGCC injection and disposal wells: http://wogcc.state.wy.us/legacywogcce.cfm
- WDEQ Cumulative Hydrologic Impact Assessments (CHIA) for coal mines: http://deq.wyoming.gov/lqd/coal/resources/chia/
- BLM Wyoming Resource Management Plans: https://www.blm.gov/programs/planning-and-nepa/plans-in-development/wyoming
- WSGS groundwater publications: http://www.wsgs.wyo.gov/water/groundwater
- The USGS Publications Warehouse: https://pubs.er.usgs.gov/

Table 10-1. Commodity and produced groundwater from energy production during 2002–2016.

	Traditional oil and gas production[1]			CBM production[1]		Injected/disposed water[1]			PRB coal production		Energy development
Year	Oil (BBLS) x 1,000	Natural gas (MCF) x 1,000	Produced water (ac-ft)	Coal Bed Gas (MCF) x 1,000	Produced water (ac-ft)	Injected Water (ac-ft)	Disposed Water (ac-Ft)	% Produced water injected/ disposed	Coal[2] (Short tons) x 1,000	Produced[3] water (ac-ft)	Total Produced water (ac-ft)
2002	20,842	81,163	58,593	326,411	74,621	47,916	2,596	38%	212,059	28,341	161,555
2003	19,567	75,637	57,406	345,749	73,001	44,321	2,960	36%	211,792	28,305	158,712
2004	18,690	76,447	54,031	332,123	69,349	41,543	3,042	36%	225,856	30,185	153,565
2005	18,670	64,373	55,535	337,142	71,876	37,403	3,088	32%	235,318	31,449	158,861
2006	18,940	54,905	49,436	377,796	87,225	31,133	3,361	25%	264,457	35,344	172,005
2007	18,581	48,036	57,749	429,935	84,559	29,056	3,514	23%	277,740	37,119	179,426
2008	17,958	48,667	57,705	536,996	88,391	26,033	3,467	20%	285,194	38,115	184,211
2009	17,592	44,522	55,211	559,046	73,295	23,972	3,634	21%	273,059	36,493	165,000
2010	19,251	39,277	58,248	539,395	68,663	25,434	4,084	23%	276,303	36,927	163,838
2011	20,855	41,383	54,466	480,556	63,241	25,292	3,846	25%	284,064	37,964	155,671
2012	23,666	47,702	51,195	401,966	48,308	21,051	4,080	25%	260,977	34,879	134,382
2013	30,835	63,564	47,820	312,910	38,951	20,290	3,798	28%	242,330	32,387	119,157
2014	41,872	82,328	43,665	246,761	33,102	18,936	3,847	30%	247,166	33,033	109,800
2015	50,668	98,754	41,443	198,996	25,568	16,699	4,193	31%	228,771	30,574	97,585
2016	38,901	94,231	42,344	155,567	22,140	14,600	3,724	28%	189,652	25,346	89,831
Total	**376,888**	**960,990**	**784,848**	**5,581,347**	**922,290**	**423,677**	**53,234**		**3,714,737**	**496,461**	**2,203,599**

[1] WOGCC, 2018

[2] U.S. Energy Information Administration, 2018

[3] Lovelace, 2009

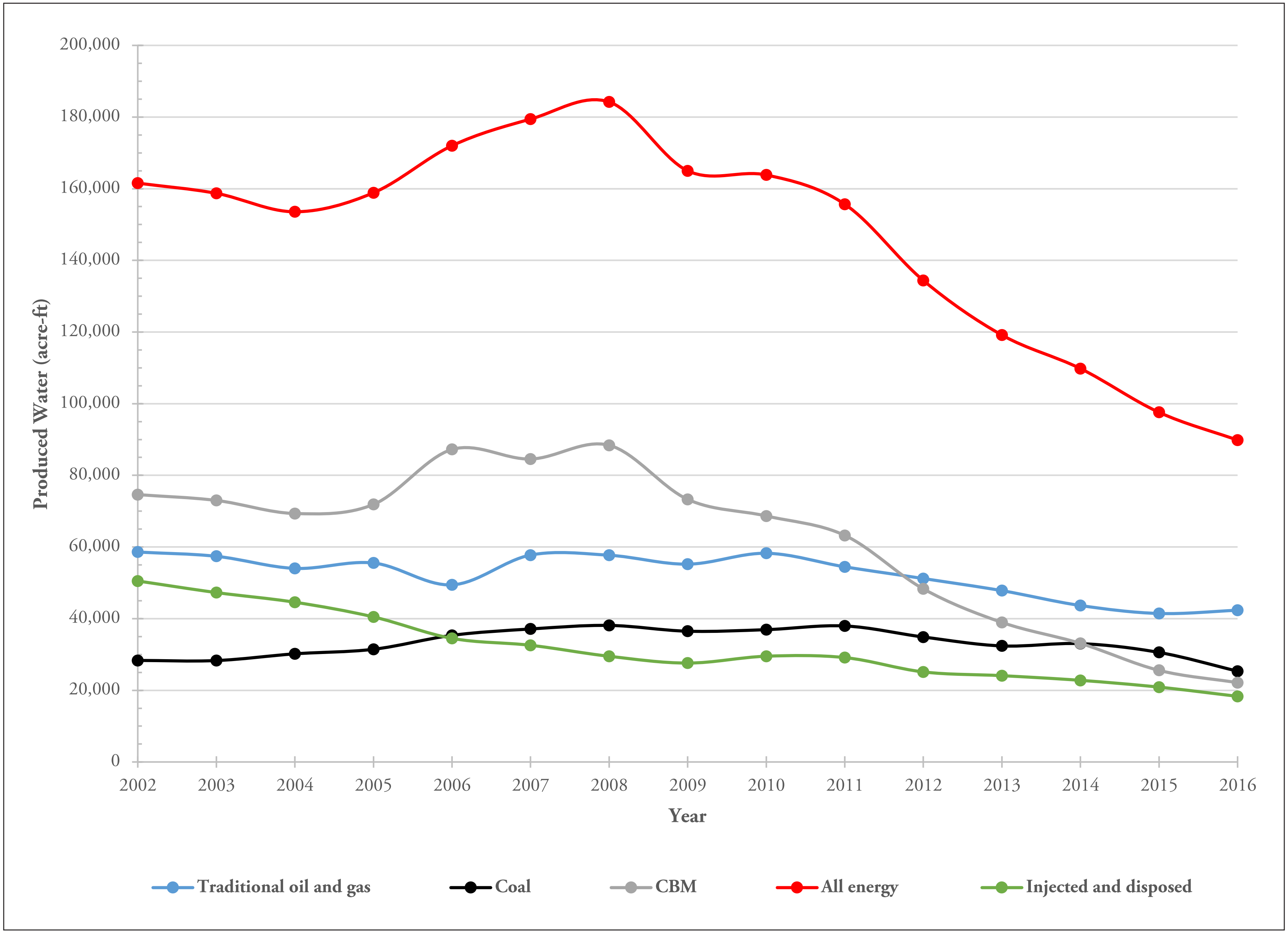


Figure 10-1. Produced water volumes from energy production during 2002–2016.

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Appendix A

Description of GIS geologic units, Northeast River Basin (NERB), Wyoming, Montana, South Dakota, and Nebraska

This appendix describes the 75 geologic units that comprise the NERB in Wyoming and portions of neighboring states, Montana (MT), South Dakota (SD), and Nebraska (NE). The descriptions of the stratigraphy in this appendix are for the units illustrated on plate 1.

The geologic units shown in plate 1 are compiled from the 1:500,000-scale statewide geologic map (Love and Christiansen, 1985). The map provides a unit code and name of the rock units within the map area. Each state has a unique set of codes; codes nor unit boundaries necessarily match across state lines. The presence and/or variation in naming convention and/or unit code of individual units in neighboring states are noted in brackets at the end of the associated description. Stratigraphic unit descriptions for adjacent states are addressed in separate sections. This appendix provides details of the physical characteristics of the rocks shown on the map as defined in that state.

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WYOMING

CENOZOIC

QUATERNARY

Qa	**ALLUVIUM AND COLLUVIUM** (Holocene-Pleistocene)—Clay, silt, sand, and gravel in flood plains, fans, terraces, and slopes [Qal in MT and SD]
Qt	**GRAVEL, PEDIMENT, AND FAN DEPOSITS** (Holocene-Pleistocene)—Mostly locally derived clasts; locally includes some Tertiary gravel [SD]
Qg	**GLACIAL DEPOSITS** (Holocene-Pleistocene)—Till and outwash of sand, gravel, and boulders
Qls	**LANDSLIDE DEPOSITS** (Holocene-Pleistocene)—Local intermixed landslide and glacial deposits, talus, and rock-glacier deposits [Ql in SD]
Qs	**DUNE SAND AND LOESS** (Holocene-Pleistocene)—Includes active and dormant sand dunes
Qu	**UNDIVIDED SURFICIAL DEPOSITS** (Holocene-Pleistocene)—Mostly alluvium, colluvium, and glacial and landslide deposits

QUATERNARY-TERTIARY

QTg	**TERRACE GRAVELS** (Pleistocene and/or Pliocene)—Partly consolidated gravel above and flanking some major streams

TERTIARY

Tmu	**UPPER MIOCENE ROCKS** (Miocene)—Light-colored tuffaceous claystone, sandstone, and conglomerate; Ogallala Formation in Denver Basin
Tml	**LOWER MIOCENE ROCKS** (Miocene)—Gray, soft, poorly bedded to massive sandstone
Tmo	**LOWER MIOCENE AND UPPER OLIGOCENE ROCKS** (Miocene and Oligocene)—Light-colored, soft, porous sandstone and underlying white tuffaceous claystone and siltstone; Arikaree Formation in Denver Basin
Twr	**WHITE RIVER FORMATION** (Oligocene)—White to pale-pink blocky tuffaceous claystone and lenticular arkosic conglomerate [Tw in NE]
Tid	**DACITE AND QUARTZ LATITE INTRUSIVE AND EXTRUSIVE IGNEOUS ROCKS** (Oligocene and/or Eocene)—Light-gray porphyritic rock
Twb	**WAGON BED FORMATION** (Eocene)—Dull-green, siliceous bentonitic claystone and tuff; giant granite boulder conglomerate in tuffaceous matrix
Tai	**ALKALIC INTRUSIVE AND EXTRUSIVE IGNEOUS ROCKS** (Eocene)—Light- to greenish-gray porphyry
Tw	**WASATCH FORMATION** (Eocene)—Drab sandstone and drab to variegated claystone; numerous coal beds in lower part [MT]
Twmo	**MONCRIEF MEMBER—**Conglomerate of Precambrian clasts, interbedded with drab sandstone and claystone
Twk	**KINGBURY CONGLOMERATE MEMBER—**Conglomerate of Paleozoic clasts, interbedded with drab sandstone and variegated claystone
Tie	**INTRUSIVE AND EXTRUSIVE IGNEOUS ROCKS** (Eocene)—Incorporates masses of Mississippian through Cambrian formations; confined to the Black Hills [Tt—Trachytic intrusive rock in SD]
Twdr	**WIND RIVER FORMATION** (Eocene)—Variegated claystone and sandstone; lenticular conglomerate
Tim	**INDIAN MEADOWS FORMATION** (Eocene)—Red to variegated claystone, sandstone, and algal-ball (?) limestone; some beds of large Paleozoic boulders and detachment masses of Paleozoic and Mesozoic rocks
Tfu	**FORT UNION FORMATION** (Paleocene)—Light-colored massive sandstone, drab shale, and thick coal beds [MT]
Tftr	**TONGUE RIVER MEMBER—**Thick beds of yellow sandstone interbedded with gray and black shale and many coal beds
Tfl	**LEBO MEMBER—**Dark-gray clay shale and concretionary sandstone
Tft	**TULLOCK MEMBER—S**oft-gray sandstone, gray and brown carbonaceous shale, and thin coal beds

Tftl	**TONGUE RIVER AND LEBO MEMBERS—**Undifferentiated; *TONGUE RIVER MEMBER*: Thick beds of yellow sandstone interbedded with gray and black shale and many coal beds; *LEBO MEMBER*: Dark-gray clay shale and concretionary sandstone
Tflt	**LEBO AND TULLOCK MEMBERS—**Undifferentiated; *LEBO MEMBER*: Dark-gray clay shale and concretionary sandstone; *TULLOCK MEMBER*: Soft-gray sandstone, gray and brown carbonaceous shale, and thin coal beds

MESOZOIC

CRETACEOUS

Kl	**LANCE FORMATION** (Upper Cretaceous)—Greenish-gray bentonitic tuffaceous sandstone and conglomerate [Khc—Hell Creek Formation in MT]
Klm	**LANCE FORMATION, FOX HILLS SANDSTONE, MEETEETSE FORMATION, AND BEARPAW AND LEWIS SHALES** (Upper Cretaceous)—Undifferentiated; *LANCE FORMATION*: Greenish-gray bentonitic tuffaceous sandstone and conglomerate; *FOX HILLS SANDSTONE*: Light-colored sandstone and gray sandy shale containing marine fossils; *MEETEETSE FORMATION*: Chalky- white to gray sand stone, yellow, green, and dark-gray bentonitic claystone, white tuff, and thin coal beds; *BEARPAW SHALE*: Dark greenish-gray shale containing thin gray sandstone partings
Kfh	**FOX HILLS SANDSTONE** (Upper Cretaceous)—Light-colored sandstone and gray sandy shale containing marine fossils [MT]
Kfl	**FOX HILLS SANDSTONE AND LEWIS SHALE** (Upper Cretaceous)—Undifferentiated; *FOX HILLS SANDSTONE*: Light-colored sandstone and gray sandy shale containing marine fossils; *LEWIS SHALE*: Gray marine shale containing many gray and brown lenticular concretion-rich sandstone beds
Kfb	**FOX HILLS SANDSTONE AND BEARPAW SHALE** (Upper Cretaceous)—Undifferentiated; *FOX HILLS SANDSTONE*: Light-colored sandstone and gray sandy shale containing marine fossils; *BEARPAW SHALE*: Dark greenish-gray shale containing thin gray sandstone partings [MT]
Kml	**MEETEETSE FORMATION AND LEWIS SHALE** (Upper Cretaceous)—Undifferentiated; *MEETEETSE FORMATION*: Chalky-white to gray sandstone, yellow, green, and dark-gray bentonitic clay stone, white tuff, and thin coal beds; *LEWIS SHALE*: Gray marine shale containing many gray and brown lenticular concretion-rich sandstone beds
Kmv	**MESAVERDE GROUP** (Upper Cretaceous)—Light-colored, massive to thin-bedded sandstone, gray sandy shale, and coal beds
Kc	**CODY SHALE** (Upper Cretaceous)—Dull-gray shale, gray siltstone, and fine-grained gray sandstone
Kf	**FRONTIER FORMATION** (Upper Cretaceous)—Gray sandstone and sandy shale
Kft	**FRONTIER FORMATION, AND MOWRY AND THERMOPOLIS SHALES** (Upper and Lower Cretaceous)—Undifferentiated; *FRONTIER FORMATION*: Gray sandstone and sandy shale; *MOWRY SHALE*: Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds; *THERMOPOLIS SHALE*: Black soft fissile shale

Kp	**PIERRE SHALE** (Upper Cretaceous)—Dark-gray concretionary marine shale; contains several bentonite beds [MT, SD, NE]
Kn	**NIOBRARA FORMATION** (Upper Cretaceous)—Light-colored limestone and gray- to yellow-specked limy shale [MT, SD]
Knc	**NIOBRARA FORMATION AND CARLILE SHALE** (Upper Cretaceous)—Undifferentiated; *NIOBRARA FORMATION*: Light-colored limestone and gray- to yellow-specked limy shale; *CARLILE SHALE*: Dark-gray sandy shale
Kcl	**CARLILE SHALE** (Upper Cretaceous)—Dark-gray sandy shale
Kg	**GREENHORN FORMATION** (Upper Cretaceous)—Light-colored limestone, marl, and limy sandstone interbedded with gray concretionary shale
Kgb	**GREENHORN FORMATION AND BELLE FOURCHE SHALE** (Upper Cretaceous)—Undifferentiated; *GREENHORN FORMATION*: Light-colored limestone, marl, and limy sandstone interbedded with gray concretionary shale; *BELLE FOURCHE SHALE*: Black soft bentonitic concretionary shale
Kgbm	**GREENHORN FORMATION AND BELLE FOURCHE AND MOWRY SHALES** (Upper and Lower Cretaceous)—Undifferentiated; *GREENHORN FORMATION*: Light-colored limestone, marl, and limy sandstone interbedded with gray concretionary shale; *BELLE FOURCHE SHALE*: Black soft bentonitic concretionary shale
Kmr	**MOWRY SHALE** (Lower Cretaceous)—Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds
Kmt	**MOWRY AND THERMOPOLIS SHALES** (Lower Cretaceous)—Undifferentiated; *MOWRY SHALE*: Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds; *THERMOPOLIS SHALE*: Black soft fissile shale
Kns	**NEWCASTLE SANDSTONE AND SKULL CREEK SHALE** (Lower Cretaceous)—Undifferentiated; *NEWCASTLE SANDSTONE*: Gray sandstone and sandy shale containing some bentonite and coal; *SKULL CREEK SHALE*: Black soft fissile shale

CRETACEOUS-JURASSIC

KJ	**CLOVERLY AND MORRISON FORMATIONS (W/SW) or INYAN KARA GROUP AND MORRISON FORMATION (E/SE)** (Lower Cretaceous-Upper Jurassic)—Undifferentiated; *CLOVERLY FORMATION*: Rusty to light-gray sandstone containing lenticular chert-pebble conglomerate interbedded with variegated bentonitic claystone; *MORRISON FORMATION*: Dully variegated siliceous claystone, nodular white limestone, and gray silty sandstone; *INYAN KARA GROUP*: Rust to light-gray sandstone containing lenticular chert-pebble conglomerate interbedded with variegated bentonitic claystone
KJs	**CLOVERLY, MORRISON, AND SUNDANCE FORMATIONS** (Lower Cretaceous-Upper Jurassic)—Undifferentiated; *CLOVERLY FORMATION*: Rusty to light-gray sandstone containing lenticular chert-pebble conglomerate interbedded with variegated bentonitic claystone; *MORRISON FORMATION*: Dully variegated siliceous claystone, nodular white limestone, and gray silty sandstone; *SUNDANCE FORMATION*: Greenish-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale

KJg **CLOVERLY, MORRISON, SUNDANCE, AND GYPSUM SPRING FORMATIONS** (Lower Cretaceous-Upper Jurassic)—Undifferentiated; *CLOVERLY FORMATION*: Rusty to light-gray sandstone containing lenticular chert-pebble conglomerate interbedded with variegated bentonitic claystone; *MORRISON FORMATION*: Dully variegated siliceous claystone, nodular white limestone, and gray silty sandstone; *SUNDANCE FORMATION*: Greenish-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale; *GYPSUM SPRING FORMATION*: Interbedded red shale, dolomite, and gypsum

JURASSIC

Jsg **SUNDANCE AND GYPSUM SPRING FORMATIONS** (Jurassic)—Undifferentiated; *SUNDANCE FORMATION*: Greenish-gray glauconitic sandstone and shale, underlain by red and gray non-glauconitic sandstone and shale; *GYPSUM SPRING FORMATION*: Interbedded red shale, dolomite, and gypsum

TRIASSIC

₸cd **CHUGWATER AND DINWOODY FORMATIONS** (Triassic)—Undifferentiated; *CHUGWATER FORMATION*: Red siltstone and shale with thin gypsum partings near base; *DINWOODY FORMATION*: Olive-drab hard dolomitic thin-bedded siltstone

₸c **CHUGWATER FORMATION** (Triassic)—Red siltstone and shale with thin gypsum partings near base

TRIASSIC-PERMIAN

₸Pcg **CHUGWATER AND GOOSE EGG FORMATIONS** (Lower Triassic-Permian)—Undifferentiated; *CHUGWATER FORMATION*: Red siltstone and shale with thin gypsum partings near base; *GOOSE EGG FORMATION*: Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone

₸Ps **SPEARFISH FORMATION** (Triassic-Permian)—Red shale, red siltstone, and white gypsum beds; gypsum beds especially abundant near base [SD]

₸Pg **GOOSE EGG FORMATION** (Lower Triassic-Permian)—Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone

PALEOZOIC

Pzr **UNDIVIDED PALEOZOIC UNITS** (Cambrian-Permian)—Undifferentiated rocks of Cambrian to Permian age

PERMIAN

Pp **PHOSPHORIA FORMATION AND RELATED ROCKS** (Permian)—Brown sandstone and dolomite, cherty phosphatic and glauconitic dolomite, phosphatic sandstone and dolomite, and greenish-gray to black shale

Pmo **MINNEKAHTA LIMESTONE AND OPECHE SHALE** (Permian)—Undifferentiated; *MINNEKAHTA LIMESTONE*: Gray slabby hard limestone; locally is a member of the Goose Egg Formation; *OPECHE SHALE*: Red, soft, sandy shale; locally is a member of the Goose Egg Formation [SD]

PERMIAN-PENNSYLVANIAN

PIPh	**HARTVILLE FORMATION** (Lower Permian-Pennsylvanian)—Red and white sandstone underlain by gray dolomite and limestone, red shale, and red and gray sandstone; lowermost unit may be Late Mississippian in age
PIPm	**MINNELUSA FORMATION** (Lower Permian-Pennsylvanian)—Buff and red limy sandstone; some thin limestone beds, solution breccias, and gypsum [SD]

PERMIAN-MISSISSIPPIAN

PM	**TENSLEEP SANDSTONE AND AMSDEN FORMATION** (Lower Permian-Upper Mississippian)—Undifferentiated; *TENSLEEP SANDSTONE*: White to gray sandstone containing thin limestone and dolomite beds. Permian fossils have been found in the topmost beds of the Tensleep at some localities in Washakie Range, Owl Creek Mountains, and southern Bighorn Mountains; *AMSDEN FORMATION*: Red and green shale and dolomite; at base is brown sandstone [PNu in MT]

MISSISSIPPIAN

Mm	**MADISON LIMESTONE OR GROUP** (Upper and Lower Mississippian)—Group includes Mission Canyon Limestone (blue-gray massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty limestone and dolomite)

MISSISSIPPIAN-DEVONIAN

MD	**MADISON LIMESTONE OR DARBY FORMATION** (Upper Mississippian-Upper Devonian)—Undifferentiated; *MADISON LIMESTONE OR GROUP*: Group includes Mission Canyon Limestone (blue-gray massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty limestone and dolomite); *DARBY FORMATION*: Yellow and greenish-gray shale and dolomitic siltstone underlain by fetid brown dolomite [Mu in MT]
MDg	**GUERNSEY FORMATION** (Lower Mississippian-Upper Devonian)—Blue-gray massive cherty limestone and dolomite; locally includes unnamed dolomite and sandstone of Devonian and Cambrian (?) age
MDe	**PAHASAPA AND ENGLEWOOD LIMESTONES** (Lower Mississippian-Upper Devonian)—Undifferentiated; *PAHASAPA LIMESTONE*: Gray massive dolomitic limestone; *ENGLEWOOD LIMESTONE*: Pink slabby dolomitic limestone [MDpe in SD]

MISSISSIPPIAN-ORDOVICIAN

MO	**MADISON LIMESTONE AND BIGHORN DOLOMITE** (Mississippian-Middle and Upper Ordovician)—Undifferentiated; MADISON LIMESTONE: Group includes Mission Canyon Limestone (blue-gray massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty limestone and dolomite); *BIGHORN DOLOMITE*: Gray massive cliff-forming siliceous dolomite and locally dolomitic limestone

ORDOVICIAN-CAMBRIAN

O€ **WHITEWOOD DOLOMITE AND WINNIPEG AND DEADWOOD FORMATIONS** (E); **OR BIGHORN DOLOMITE, GALLATIN LIMESTONE, GROS VENTRE FORMATION, AND FLATHEAD SANDSTONE (W)** (Upper Ordovician-Upper/Middle Cambrian)—Undifferentiated; *WHITEWOOD DOLOMITE*: Buff massive fossiliferous dolomite; *WINNIPEG FORMATION*: Pink to yellow siltstone and shale; *DEADWOOD FORMATION*: Red and brown quartzite sandstone; *BIGHORN DOLOMITE*: Light-gray massive siliceous dolomite; *GALLATIN LIMESTONE*: Blue-gray and yellow mottled hard dense limestone; *GROS VENTRE FORMATION*: Soft-green micaceous shale (Upper and Middle Cambrian Park Shale Member), underlain by blue-gray and yellow mottled hard dense limestone (Middle Cambrian Death Canyon Limestone Member), and soft-green micaceous shale (Middle Cambrian Wolsey Shale Member); *FLATHEAD SANDSTONE*: Dull-red quartzite sandstone [Ou in MT; O€wd in O€wd in SD]

ORDOVICIAN

Ob **BIGHORN DOLOMITE** (Upper and Middle Ordovician)—Light-gray massive siliceous dolomite

CAMBRIAN

€r **CAMBRIAN ROCKS** (Cambrian)—Blue-gray and yellow mottled hard dense limestone interbedded with soft-green micaceous shale; dull-red quarzitic sandstone at base

PRECAMBRIAN

EARLY PROTEROZOIC

Xsv **METASEDIMENTARY AND METAVOLCANIC ROCKS** (Proterozoic)—Pelitic schist; includes minor amounts of granite and amphibolite [XWgw in SD]

ARCHEAN

Wmu **METASEDIMENTARY AND METAVOLCANIC ROCKS** (Late Archean)—Amphibolite

Wg **GRANTITIC ROCKS OF 2,600-MA AGE GROUP** (Late Archean)—Granite and minor amounts of metasedimentary rocks

Wvsv **METASEDIMENTARY AND METAVOLCANIC ROCKS** (Late to Middle Archean)—Amphibolite, hornblende gneiss, biotite gneiss, quartzite, iron-formation, metaconglomerate, marble, and pelitic schist; locally preserved textures and structure suggest origin to be sedimentary or volcanic

WVg **PLUTONIC ROCKS** (Late to Middle Archean)—Quartz diorite to quartz monzonite

Ugn **OLDEST GNEISS COMPLEX** (Early Archean)—Chiefly layered granitic gneiss, locally migmatitic; local masses of quartzite, metagraywacke, iron-formation, and other metasedimentary rocks, amphibolite, and felsic gneiss through to be volcanic; dates of metamorphism in the Bighorn Mountains 3,000+ Ma

MONTANA

CENOZOIC

QUATERNARY

Qal	**ALLUVIUM** (Quaternary)—Mainly valley fill consisting of silt, sand, and gravel; includes terrace deposits and glacial drift of Pleistocene age in some areas; locally includes hot spring tufa; the older part of the alluvium, where present, is probably of Pliocene age [SD, Qa in WY] [SD, Qa in WY]

TERTIARY

Tw	**WASATCH FORMATION** (Tertiary)—Light-colored massive sandstone; drab-colored shale and coal in southeastern Montana; variegated, dominantly red beds of clay and sandstone in north-central Montana [WY]

TERTIARY-CRETACEOUS

Tfu	**FORT UNION FORMATION** (Tertiary-Cretaceous)—Clay shale, siltstone, and sandstone; local lenses of impure limestone and numerous lignitic beds; contains Tertiary plant and animal fossils but no dinosaurs; base generally placed at the lowest of the succession of lignite beds within it; includes the Tongue River, Lebo shale, and Tullock members [WY]

MESOZOIC

CRETACEOUS

Khc	**HELL CREEK FORMATION** (Cretaceous-Late Tertiary)—Somber-gray sandstone and greenish shaly clay and mudstone containing dinosaur bones; a few thin lignite and subbituminous coal beds [Kl—Lance Formation in WY]
Kfh	**FOX HILL SANDSTONE** (Late Cretaceous)—Typically shaly sandstone grading upward into massive brownish sandstone with white sandstone of the Colgate member locally at top [WY]
Kp	**PIERRE SHALE** (Late Cretaceous)—Dark-gray clay shale with calcareous and ferruginous concretions and sandy members [SD, NE, WY]
Kfb	**FOX HILL SANDSTONE AND BEARPAW SHALE** (Late Cretaceous)—Undifferentiated; *FOX HILL SANDSTONE*: Typically shaly sandstone grading upward into massive brownish sandstone with white sandstone of the Colgate member locally at top; *BEARPAW SHALE*: Dark-gray and brownish clay shale; thick units of non-fissile bentonitic shale; calcareous and ferruginous concretions throughout; contains thick bentonite beds [WY]
Kjr	**JUDITH RIVER FORMATION** (Late Cretaceous)—Light-colored sandstone at top; lower third somber-gray siltstone and sandy shale; greenish-gray clay and some lignite beds; includes the Parkman sandstone member of south-central Montana
Kn	**NIOBRARA FORMATION** (Late Cretaceous)—Chiefly calcareous shale with limestone concretions; many thin bentonite beds locally [SD, WY]

Kce **CARLILE SHALE** (Late Cretaceous)—Dark-gray shale with calcareous and ferruginous concretions; middle part commonly sandy

Kg **GREENHORN FORMATION** (Late Cretaceous)—Mainly light-gray marl and calcareous shale [SD]

Kbf **BELLE FOURCHE SHALE** (Cretaceous)—Dark blue-gray siliceous shale with many calcareous and ferruginous concretions and intercalated thin layers of bentonite [Kb in SD] [Kb in SD]

Kmo **MOWRY SHALE** (Early Cretaceous)—Chiefly light-gray silicified shale and claystone with minor amounts of sandy shale and sandstone; contains some thick beds of bentonite

TRIASSIC

TRu **TRIASSIC, UNDIFFERENTIATED** (Triassic)—Conglomerate, sandstone, shale, and impure limestone belonging to the Dinwoody and Thaynes formations and other units of Triassic age, and the Chugwater of Triassic and Permian age

PALEOZOIC

PERMIAN-MISSISSIPPIAN

PNu **PENNSYLVANIAN, UNDIFFERENTIATED** (Pennsylvanian)—In western Montana is mainly the Quadrant quartzite but includes limestone and other rocks of Pennsylvanian age so far as present data permit; farther east, other formations of Pennsylvanian or possible Pennsylvanian age are included [PM—Tensleep Sandstone and Amsden Formation in WY] [PM—Tensleep Sandstone and Amsden Formation in WY]

MISSISSIPPIAN

Mu **MISSISSIPPIAN, UNDIFFERENTIATED** (Mississippian)—Sandstone, shale, and limestone, in part dolomitic, with chert nodules, some quartzite, includes Big Snowy group in central part of Montana, Madison Group in central and southwestern parts, and Hannan and Brazer Limestones in the northwestern part; may include small amounts of Pennsylvanian rocks in areas where stratigraphic studies are incomplete [Mm—Tensleep Sandstone and Amsden Formation in WY]

ORDOVICIAN

Ou **ORDOVICIAN, UNDIFFERENTIATED** (Ordovician)—Mainly Bighorn dolomite; near Idaho, Kinnikinic quartzite [Ob in WY]

SOUTH DAKOTA

CENOZOIC

QUATERNARY

Qal **ALLUVIUM** (Quaternary)—Clay to boulder-size clasts with locally abundant organic material [MT; Qa in WY]

Qt **TERRACE DEPOSITS** (Quaternary)—Clay to boulder-size clasts deposited as pediments, paleochannels, and terrace fills of former flood plains [WY]

Ql **LANDSLIDE DEPOSITS** (Quaternary)—Landslide, slump, and collapsed material composed of chaotically mixed boulders and finer- grained rock debris [Qls in WY]

TERTIARY

Tt **TRACHYTIC INTRUSIVE ROCKS** (Paleocene-Eocene)—Tan to reddish-brown, iron-stained stocks, laccoliths, sills, and dikes of trachyte, quartz trachyte, and alkalic rhyolite; contains phenocrysts of sanidine, orthoclase, anorthoclase, aegirine-augite, and biotite in a finely-crystalline orthoclase-quartz biotite groundmass [Tie —Intrusive and extrusive igneous rocks in WY]

MESOZOIC

CRETACEOUS

Kp **PIERRE SHALE** (Late Cretaceous)—Blue-gray to dark-gray, fissile to blocky shale with persistent beds of bentonite, black organic shale, or light-brown chalky shale. Contains minor sandstone, conglomerate, and abundant carbonate and ferruginous concretions [NE, WY, MT]

Kn **NIOBRARA FORMATION** (Late Cretaceous)—White to dark-gray argillaceous chalk, marl, and shale; weathers yellow to orange; contains thin, laterally continuous bentonite beds, chalky carbonaceous shale, minor sand, and small concretions [WY, MT]

Kg **GREENHORN FORMATION** (Late Cretaceous)—Gray shale, mudstone, marl, calcarenite, and shaley limestone grading upward into light-gray to tan, alternating marl and thin-bedded, fossiliferous limestone [MT]

Kb **BELLE FOURCHE SHALE** (Late Cretaceous)—Dark-gray to black bentonitic shale containing minor limestone lenses, bentonite layers, fossiliferous calcarenite, and large, ferruginous, carbonate concretions [Kbf in MT]

Kms **MOWRY SHALE, NEWCASTLE SANDSTONE, AND SKULL CREEK SHALE** (Early Cretaceous)—Undifferentiated; MOWRY SHALE: Black to gray, siliceous, fissile shale, and siltstone containing bentonite layers, and sparse sandstone dikes and sills; *NEWCASTLE SANDSTONE*: Gray, light-brown to yellow, discontinuously distributed siltstone, claystone, sandy shale, and fine-grained sandstone; *SKULL CREEK SHALE*: Dark-gray to blueish-gray shale containing ferruginous and carbonate concretions

Kfl **INYAN KARA GROUP** (Early Cretaceous)—Includes: *FALL RIVER FORMATION*: Variegated brown, red, gray to purple, calcareous, well-sorted, fine-grained sandstone, siltstone, and shale containing mica flakes; *LAKOTA FORMATION*: Yellow, brown, red-brown, gray to black silty shale, pebble conglomerate, and massive to thin-bedded, cross-bedded sandstone; locally interbedded with fresh-water limestone and bituminous coal beds

JURASSIC

Jms **MORRISON FORMATION, UNKPAPA SANDSTONE, SUNDANCE FORMATION, AND GYPSUM SPRING FORMATION** (Middle-Late Jurassic)—Undifferentiated; *MORRISON FORMATION* (Late Jurassic): Light-gray to green and variegated red, brown, yellow, or lavender, siliceous claystone, shale, and siltstone containing interbedded sandstone and fresh-water limestone lenses; *UNKPAPA SANDSTONE* (Late Jurassic): White, massive to thin-bedded, fine-grained, argillaceous sandstone; may be variegated to banded red, yellow, brown, or lavender; *SUNDANCE FORMATION* (Late to Middle Jurassic): Greenish-gray, yellow, tan, red to orange, and white, variegated, interbedded, fine- to coarse-grained sandstone, siltstone, clay, and limestone; *GYPSUM SPRING FORMATION* (Middle Jurassic): Massive white gypsum and minor maroon siltstone and shale

TRIASSIC-PERMIAN

TRPs **SPEARFISH FORMATION** (Permian-Triassic)—Red sandy shale, siltstone, sandstone, and minor limestone; interbedded with abundant gypsum [WY]

PALEOZOIC

PERMIAN

Pmo **MINNEKAHTA LIMESTONE AND OPECHE SHALE** (Permian)—Undifferentiated; *MINNEKAHTA LIMESTONE*: Purple to gray, finely-crystalline, thin- to medium-bedded limestone with varying amounts of red shale; *OPECHE SHALE*: Red siltstone, argillaceous sandstone, and shale interbedded with caliche layers [WY]

PERMIAN-PENNSYLVANIAN

PIPm **MINNELUSA FORMATION** (Pennsylvanian-Permian)—Variegated, yellow to red, gray to brown, pink to purple, and black, interbedded sandstone, siltstone, shale, limestone, dolomite, calcarenite, chert and brecciated beds [WY]

MISSISSIPPIAN-DEVONIAN

MDpe **MADISON GROUP** (Devonian-Mississippian)—Includes: *PAHASAPA LIMESTONE* (Mississippian): White, light-gray to tan, fine- to medium-crystalline limestone and dolomite containing brown to gray chert; solution features including collapse breccia, sinkholes, and caves are prevalent; *ENGLEWOOD FORMATION* (Mississippian to Devonian): Pink, lavender to light-gray, thin- to medium-bedded, finely-crystalline, argillaceous, dolomitic limestone [MDe —Pahasapa and Englewood limestones in WY]

ORDOVICIAN-CAMBRIAN

O€wd **WHITEWOOD LIMESTONE, WINNIPEG FORMATION, AND DEADWOOD FORMATION** (Ordovician-Cambrian)—Undifferentiated; *WHITEWOOD LIMESTONE* (Ordovician): Mottled, tan, gray to lavender, fine- to medium-crystalline, sparsely fossiliferous limestone, and dolomite; *WINNIPEG FORMATION*: (Ordovician): Gray and light-green, fissile shale, and tan, calcareous siltstone, sandy shale, and limestone lenses; *DEADWOOD FORMATION* (Ordovician to Cambrian): Variegated, yellow to red, brown, gray, and green, glauconitic, conglomerate, sandstone, shale, dolomitic limestone, and dolomite [O€ in WY; Ou in MT] [O€ in WY; Ou in MT]

EARLY PROTEROZOIC-ARCHEAN

XWp **PEGMATITE** (Archean(?)-Paleoproterozoic)—Light-tan to pink pegmatite

XWb **METABASALT** (Archean(?)-Paleoproterozoic)—Dark-green amphibolite and amphibolite schist

XWgw **METAGRAYWACKE** (Archean(?)-Paleoproterozoic)—Gray, siliceous mica schist and impure quartzite [Xsv in WY]

NEBRASKA

CENOZOIC

TERTIARY

Ta **ARIKAREE GROUP** (Oligocene-Miocene)—Consists mainly of gray, fine, loose to compact sand that has layers of hard, fine-grained dark-gray concretions, which vary from a few inches to 15 inches and commonly have tabular form; includes a large amount of volcanic ash mixed in with the sand; contains a number of channels filled with coarse conglomerate along ridge south of North Platte River

Tw **WHITE RIVER GROUP** (Oligocene)—Clay, some claystone, silt and siltstone; predominantly greenish gray and volcaniclastic; other occurrences are greenish gray to white and bentonitic; local channel sandstone at base [Twr in WY]

CRETACEOUS

Kp **PIERRE SHALE** (Late Cretaceous)—Mostly medium- to dark-gray, brownish-gray, and black, fissile clay shale; locally grades to thin beds of calcareous, silty shale or claystone, marl, shaly sandstone, and sandy shale; locally contains thin seams of gypsum and sparse selenite crystals [WY, MT, SD]

Appendix B

WWDC groundwater studies

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Wyoming River Basins				
Wyoming Water Planning Program, 1973, Wyoming's groundwater supplies: Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, [variously paged].	All aquifers	Summary of available groundwater and groundwater sources.	Predictions of aquifer water quantity throughout the state of Wyoming.	Statewide river basin water planning process continues.
WWC Engineering, Inc. (in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation), 2007, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged].	All aquifers	Summary of surface water and groundwater resources.	Estimates quantities of Wyoming's available water resources.	Wyoming Framework Water Plan completed.
Powder/Tongue/Northeast Basins				
HKM Engineering Inc. (in association with Lord Consulting and Watts and Associates), 2002a, Powder/Tongue river basin plan final report and technical memoranda: prepared for Wyoming Water Development Commission Basin Planning Program, [variously paged]. Executive summary and technical memoranda are available under separate cover.	All aquifers	Develop basin plans with participation from local interest groups that provide defensible hydrologic data to quantify surface water and groundwater uses.	Current surface water and groundwater uses, water quality, future demand projects, and future water use opportunities quantified and discussed. Continue planning process with updates every five years.	River basin water planning process continues.
HKM Engineering Inc. (in association with Lord Consulting and Watts and Associates), 2002b, Northeast Wyoming river basins plan final report and technical memoranda: prepared for Wyoming Water Development Commission Basin Planning Program, [variously paged]. Executive summary and technical memoranda are available under separate cover.	All aquifers	Develop basin plans with participation from local interest groups that provide defensible hydrologic data to quantify surface water and groundwater uses.	Current surface water and groundwater uses, water quality, future demand projects, and future water use opportunities quantified and discussed. Continue planning process with updates every five years.	River basin water planning process continues.
Aladdin and Beulah				
Soda Butte Services, Inc., 1994, Aladdin water supply project level I, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Madison Limestone	Assess adequacy of Madison aquifer to meet Aladdin's and Beulah's water supply requirements. Analyses of water rights, infrastructure, and economics. Provide conceptual design for separate municipal wells in each town, cost estimates, and funding options.	Madison aquifer should provide suitable water supplies to Aladdin Water District and Town of Beulah. Development of PWSs sourced from Madison municipal wells is technically and economically feasible. Proceed to Level II.	For Aladdin, see below. See Beulah on next page.
Soda Butte Services, Inc. (in association with Wester-Wetstein & Assoc., Inc.), 1995, Well construction, testing and conceptual design for the Aladdin water supply project level II, final report and summary: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Madison Limestone	Level II report to evaluate the hydrogeology of aquifer in Aladdin area, determine depth to groundwater and aquifer thickness, complete and test new municipal well, and assess groundwater quality.	AWD-1 well in Madison aquifer was completed, developed, and tested for aquifer hydraulics and water quality in Aladdin. PWS project is technically feasible. Level III design and construc-tion should proceed if Water District members approve monthly costs.	Aladdin uses the well under an agreement with WWDC.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Belle Fourche River Watershed				
RESPEC (in association with Anderson Consulting Engineers, Inc.), 2015, Belle Fourche River watershed study, basin wide watershed management plan, final report– Topical report RSI-2501: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. Executive summary is available under separate cover. RESPEC (in association with Anderson Consulting Engineers, Inc.), 2015, Belle Fourche River watershed study, Redwater subbasin watershed management plan– Topical report RSI-2514: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. RESPEC (in association with Anderson Consulting Engineers, Inc.), 2015, Belle Fourche River watershed study, subbasin above Keyhole Reservoir watershed management plan–Topical report RSI-2512: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. RESPEC (in association with Anderson Consulting Engineers, Inc.), 2015, Belle Fourche River watershed study, subbasin below Keyhole Reservoir watershed management plan –Topical report RSI-2513: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Alluvial depoits; Wasatch, Fort Union, and Inyan Kara Formations, Minnelusa and Madison Limestones	The four projects, shown at left, are watershed studies in the Belle Fourche drainage and Redwater Creek subbasin. Although the focus is on surface water, these reports provide overviews of commonly used aquifers in the Belle Fourche Basin and a brief discussion of groundwater impacts from CBM development. Figures include maps of springs and SEO permitted wells in the Belle Fourche Basin and its subbasins.	No recommendations regarding groundwater resources.	All reports are completed.
Beulah				
Weston Engineering, Inc. (in association with EnTech, Inc.), 2003, Beulah level I water supply study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Madison Limestone	Evaluate existing water supply, demands, and facilities. Provide conceptual designs for regional water system, cost estimates, and financing plans.	Madison aquifer will likely provide sufficient quantities of good-quality water to residents of Beulah. Likely well sites and service areas identified. Conceptual designs and cost estimates provided for three alternative distribution systems.	Beulah is not served by a municipal well.
Buffalo				
Plains Engineering, 1982, Buffalo hydrogeologic reconnaissance: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison, Wasatch, and Moncrief Formations; scoria deposits, Clear Creek Alluvium, Cretaceous sandstones, Paleozoic limestones	Hydrogeologic reconnaissance of 10-mile radius around Buffalo searching for a good-quality groundwater source adequate to meet 7 cfs peak demand.	There is no single source of groundwater available that can meet the water quality and quantity requirements of Buffalo.	Project completed.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Buffalo (cont.)				
Western Water Consultants, 1982, Municipal water supply study for the City of Buffalo, Wyoming level I reconnaissance study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison, Wasatch, and Morcrief Formatins; scoria deposits, Clear Creek Alluvium, Createaceous sandstones, Paleozoic limestones	Level I study to identify available options to develop cost effective supplemental water supplies.	Groundwater development is not a viable option at the time of the report to supplement Buffalo's water supplies.	Project completed.
WWC Engineering, 2011, Buffalo northwest water supply level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Unspecified Buffalo area aquifers that provide insufficient supplies from poorly producing, low-quality wells	Level I study to evaluate feasibility of connecting a likely development area northwest of Buffalo to the City's water distribution system. The area has insufficient supplies from poorly producing, low-quality wells.	Population and future water demands were projected. Design options for new large water lines connecting NW Buffalo to the City's existing PWS were presented. Cost estimates were provided for each option.	Proceeded to Level III; project completed in 2014.
WWC Engineering, 2015, Buffalo master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Unspecified Buffalo area aquifers that provide insufficient supplies from poorly producing low-quality wells	Level I study to evaluate feasibility of connecting surrounding areas to Buffalo Rural Area Supply System (BRASS). Residences in these areas obtain insufficient water supplies from poorly producing, low-quality wells.	Population and future water demands were projected. Design options for new transmission lines connecting target areas to BRASS were presented. Cost estimates were provided for each option.	At the time of this report, WWDC was funding a Level II Buffalo Groundwater Supply Study.
Cambria-Sweetwater				
Camp Creek Engineering, Inc. (in association with Wyoming Groundwater), 2015, Cambria/Sweetwater water supply level II feasibility study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Evaluate new water storage tank for Cambria and a transmission line for Sweetwater from Newcastle. These improvements would support the development of a regional water system sourced from Madison aquifer wells in Newcastle, (see Newcastle).	Cambria should negotiate with Newcastle for water supply and install a new storage tank. Sweetwater should consider purchasing water from Cambria or drill a Madison well.	Cambria purchases municipal water from Newcastle. Sweetwater's primary water source is a reservoir via the Horton Pipeline.
Campbell County				
Murphy, R.P., and Stockdale, R.G. (Wyoming State Engineer's Office), 2000, Campbell County coal bed methane monitor well program: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union and Wasatch aquifers	Report outlines the WSEO Campbell County Coal Bed Methane Monitoring Program, initiated in 1998 by the Wyoming State Legislature. Monitoring was intended to assess the effects of CBM development on the Fort Union and Wasatch aquifers.	Report describes monitoring wells installed to date and recommends additional wells be installed to form a regional monitoring well network.	Additional SEO monitoring wells were installed. Some have since been decommissioned in response to declines in CBM production.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Clear Creek				
States West Water Resources Corporation (in association with DOWL HKM, Anderson Consulting Engineers, Inc., RJH Consultants, Inc., Western Ecosystems Technology, Inc., and Watts and Assoc., Inc.), 2011, Clear Creek watershed level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary and appendices are available under separate cover.	Quaternary alluvial, Fort Union, Wasatch, Fox Hills, Lance, Dakota, Madison	Study examines the potential for developing surface water in the Clear Creek watershed but also describes commonly used aquifers. Tables list lithology, hydraulic characteristics, water quality, and development potential for five aquifer systems, listed at left.	Best prospects for water development lie with developing new reservoirs projects along Clear Creek.	At the time of this report, WWDC was funding a Level II Clear Creek Storage Study.
Clearmont				
Weston Engineering, Inc., 2008, Final report for the Clearmont CBM impact level I study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union/Wasatch aquifer system	Level I study evaluates existing Clearmont water supply and sustainability of municipal wells under three CBM development scenarios. Study concludes that due to high water to CBM production ratio, CBM production will decrease and water levels in municipal wells will remain consistent.	Obtain weekly static water levels and monitor specific capacities in municipal wells. Submit annual well data reports to SEO. Apply to WWDC for Level II study for a new well to replace Clearmont Well No. 1.	CBM production has declined in recent years. Clearmont is currently funded for a WWDC Level II project – Clearmont Test Well Study.
Cook Road				
HKM Associates, 1992, Final report for a proposed water supply system for Cook Road Water District, Campbell County, Wyoming: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union aquifer	Level I study to define existing water supply and system facilities, water supply needs, and alternatives. Identify water source with sufficient quantity and quality to meet current and future demands.	A deep Fort Union well could provide sufficient quantities of good-quality water. Exploratory drilling program recommended with well construction and delivery system cost estimates.	See below.
Soda Butte Services, Inc. (in association with Wester-Wetstein & Assoc., Inc.), 1994, Construction and testing of CRWD-1 well and conceptual design and cost estimation for Cook Road water supply project level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union aquifer	Described drilling, completion and testing of CRWD-1 test well in the Fort Union aquifer and water quality testing. Includes conceptual designs and cost estimates for remaining well construction and delivery system.	CRWD-1 well can yield 85 gpm continuously. Water quality meets SDWA standards except for radium, TDS, iron, and turbidity.	Cook Road is scheduled to connect to the Gillette Regional Water Supply.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Crestview-Antelope Valley				
Wester-Wetstein & Associates, 1999, Crestview/ Antelope Valley water supply project level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union aquifer	Level II study examines existing water supply, distribution, and storage systems of the Crestview Improvement and Service District and the Antelope Valley Improvement and Service District. Identify water source with sufficient quantity and quality to meet current and future demands of both communities.	Crestview water system should connect to Antelope Valley PWS while Crestview Well No. 1 is rehabilitated. Antelope Valley should sell water to Crestview. Existing Antelope Valley Well No.1 should be plugged and abandoned. Well No. 2 will become lead well, with No. 3 as a backup. Make improvements to storage tanks.	Crestview obtains water from Well #1 and purchases water from Antelope Valley, which obtains water from four Fort Union wells. Both subdivisions are scheduled to connect to Gillette Regional Water Supply.
Dayton				
EnTech, Inc. (in association with Environmental Design Engineering), 2000, Dayton master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Tongue River alluvium and unidentified geologic units	Level I and II studies examine existing water supply, distribution, and storage systems in Dayton, Ranchester, and Tongue River Valley.	The potential for groundwater development in the area of interest is restricted by the lack of high-yield wells. Surface water resources should be further developed to meet future demands.	Projects completed.
EnTech, Inc. (in association with Environmental Design Engineering), 2001, Final report for Dayton Water supply project level II study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary and appendix are available under separate cover.				
EnTech, Inc. (in association with Weston Engineering, Inc.), 2003, Final report for Dayton groundwater exploration project: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison Limestone and Bighorn Dolomite	At Dayton's request, an exploration well was drilled to 2,600 ft bgs and completed in the Madison and Bighorn aquifers.	Maximum flow rate is 75 gpm; maximum pump rate is 275 gpm; water quality met all primary and secondary SDWA standards. Post treatment productivity increased to max flow rate of 225 gpm, and maximum pump rate is 650 gpm.	Project completed.
EnTech, Inc. (in association with Weston Engineering, Inc.), 2004, Final report for Dayton groundwater exploration project acid enhancement program level II study supplement: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison Limestone and Bighorn Dolomite	Well was acid fractured to enhance productivity. Water delivery alternatives and costs were provided.	Dayton should use well to meet present and future water supply demands. A water conveyance system should be constructed to pump water directly from the well to the existing PWS.	Dayton obtains municipal water from the Tongue River and the Dayton #1 well.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Edgerton-Midwest				
TriHydro Corporation (in association with Banner Assoc. Inc.), 1988, Water supply project for the towns of Edgerton and Midwest, report of investigation: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Wasatch, Fort Union, Fox Hills, Tensleep, Madison aquifers	Study evaluates existing water system, and provides improvement alternatives, cost estimates, financing options, and permitting requirements. The Edgerton-Midwest No. 1 test well was drilled and completed in the Madison aquifer and tested.	WQ and aquifer hydraulics are poor in the Wasatch, Fort Union, and Fox Hills aquifers. Water quality in the Madison test well was good, but production was too low. WWDC declined to continue with project.	Project completed.
Worthington, Lenhart, Carpenter & Johnson (in association with Western Water Consultants, Inc., and Western Research Corporation), 1988, Edgerton/Midwest water supply project level II conceptual design report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Split Rock aquifer	This study briefly mentioned the Split Rock aquifer.	Study concluded groundwater development was not an economic option.	Project completed.
Worthington, Lenhart, Carpenter & Johnson (in association with Western Water Consultants, Inc.), 1989, Edgerton/Midwest water supply project level II conceptual design report task 15: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Tensleep, Wasatch, Fort Union, Fox Hills, and Madison aquifers	This report is an addendum to the previous report cited. It examines water development potential in the five aquifers listed at left.	A Madison aquifer supply is the most economical alternative, but monthly cost to residents is still higher than acceptable.	Project completed.
Western Water Consultants, 1990, Pre-design report and cost estimates for the Edgerton-Midwest reverse osmosis plant: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fox Hills aquifer	Report discusses reverse osmosis treatment for the town's existing Fox Hills aquifer municipal wells.	Cost of treatment is lower than other alternatives, but per capita cost would still be high.	Edgerton and Midwest purchase water from the Central Wyoming Regional Water System.
Gillette				
James M. Montgomery, Consulting Engineers, 1992, City of Gillette Madison well field, Well M-3 enhancement: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison aquifer	Report describes production and water quality enhancement of Well M-3 in the Madison aquifer by hydraulic fracturing with sand proppant.	Well production was greatly improved, and levels of fluoride, sodium, and chloride decreased following enhancement.	Project completed.
HKM Associates, 1993, Phase I interim report for Gillette area master plan, Gillette, Wyoming: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union, Fox Hills-Lance, Wasatch, and Madison aquifers	Predesign level study evaluates existing water system, and provides improvement alternatives and cost estimates, financing options, and permitting requirements.	Madison aquifer is most likely target for future development to supplement municipal water supplies. Gillette should develop a regional water supply system.	Project completed.
HKM Associates, 1993, Phase II final report for Gillette area master plan, Gillette, Wyoming: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union, Fox Hills-Lance, Wasatch, and Madison aquifers	Supplement to previous report discusses population and service areas, improvement alternatives, cost estimates, and financing options in greater depth.	Specifies development of Gillette Regional Water System.	Project completed.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Gillette (cont.)				
Wester Wetstein & Associates, 1994, Report for Gillette wells project level II feasibility study-rehabilitation: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union, Fox Hills-Lance, and Madison aquifers	Report evaluates condition of municipal wells and assesses what rehabilitative efforts should be conducted.	Rehabilitation of selected municipal wells will increase production. City should proceed with improvements to pipeline from Madison well field.	Project completed.
Wyoming State Engineer's Office, 1995, Fort Union Formation aquifer monitoring plan and preliminary aquifer management plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Fort Union aquifer	Document outlines the development of a monitoring program for Gillette's Fort Union municipal wells and provides a preliminary aquifer management plan.	Continue collecting water level data in monitoring well network. Start WQ monitoring during regular intervals. Install new wells to the monitoring network in the future.	Project completed.
Wester Wetstein & Associates, 2004, Coal bed methane-aquifer storage and retrieval project level II southern Ft. Union well field exploration program and development study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Interim report and executive summary are available under separate cover.*	Fort Union aquifer	Report focuses on development of a new Fort Union municipal well field south of Gillette. Well field design, water rights review, water treatment, operational plan, construction costs, and project schedule are included in the report.	Exploratory well was drilled fully penetrating Fort Union aquifer. WQ met SDWA standards. Higher than expected transmissivity (1,700 gpd/ft) indicates the well would meet productivity requirements.	Project completed.
HDR Engineering, Inc., 2009, Gillette regional master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Master plan to investigate feasibility of forming a regional water system.	Recommends formation of a regional water system sourced from further development of the Madison aquifer well field.	Gillette has developed a series of Fort Union, Fox Hills and Madison aquifer wells into the Gillette Regional Water Supply, which supplies municipal water to other cities, towns, and subdivisions in northeast Wyoming.
WLC Engineering, Surveying & Planning (in association with Weston Groundwater & Engineering), 2012, Gillette regional connections 2 level II study, Peoples Improvement & Service District, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Unknown
EnTech, Inc. (in association with Weston Groundwater & Engineering and West Plains Engineering, Inc.), 2013, Gillette regional connections 1 level II study, Bennor Estates connection, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Subdivision connected to Gillete Regional Water Supply in 2016.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Gillette (cont.)				
WLC Engineering, Surveying & Planning (in association with Weston Groundwater & Engineering), 2013, Gillette regional connections 2 level II study, South Fork Estates Improvement and Service District, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Subdivision connected to Gillete Regional Water Supply.
WLC Engineering, Surveying & Planning (in association with Weston Groundwater & Engineering), 2013, Gillette regional connections 2 level II study, Freedom Hills Improvement and Service District, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Subdivision scheduled to connect to Gillete Regional Water Supply.
EnTech, Inc. (in association with Weston Groundwater & Engineering and West Plains Engineering, Inc.), 2013, Gillette regional connections 1 level II study, Antelope Valley Connections, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Subdivision scheduled to connect to Gillete Regional Water Supply.
DOWL (in association with Weston Groundwater & Engineering), 2015, Gillette regional connection level II study, Means first extension master plan, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union and Madison aquifers	Evaluation of existing water system, and assessment of infrastructure required and construction costs associated with connection to the the Gillette Regional Water System.	Recommends infrastructure and financial alternatives to connect to Gillette Regional Water System.	Unknown
Hidden Hills				
EnTech, Inc., 2001, Final report for Hidden Hills water system level I study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Wasatch, Fort Union, Lance bedrock aquifers, and Prairie Dog Creek alluvium	Level I study to determine feasibility of establishing a PWS for the Prairie Dog Creek Valley.	Low production in Wasatch and Fort Union wells (max 20 gpm), depth of Lance (~5,000 ft bgs) and surface/groundwater connections in alluvium preclude use of groundwater in PWS. Community should seek connection with Sheridan Area Water Supply system.	Most of the Hidden Hills Area is outside of the SAWS service area. There are no records of a subdivision well in the SEO or PWS in the EPA databases.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Kaycee				
Western Water Consultants, 1983, Ground water feasibility study for Kaycee: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Tensleep Sandstone, Madison Limestone, and Bighorn Dolomite	Study to evaluate groundwater development potential, define existing and future water demands in Kaycee, identify favorable drilling sites, and provide designs and cost estimates.	Three sites were identified for Paleozoic aquifer test wells. Designs and costs for test wells were provided.	Drill and test exploratory well. See below.
Western Water Consultants, 1984, Final report on drilling and testing of the Town of Kaycee Madison #1 test well, Johnson County, Wyoming: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Tensleep and Madison aquifers	Report describes construction and testing of Kaycee Madison Test Well #1.	Test well was installed in the Tensleep Sandstone and Madison Limestone. Transmissivity of the well was estimated at 2,300 gpd/ft. WQ did not exceed any SDWA standards.	Well is now Kaycee Well #1 (P69394W).
Grizzly Engineering, Inc., 1999, Town of Kaycee water supply master plan level I: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Tensleep and Madison aquifers	Evaluation of existing water system, improvement alternatives, and cost estimates, financing options, and permitting requirements. Contains completion report for Kaycee Well #2.	Consultant suggested upgrades to existing system and extending service to Kaycee rural communities.	Kaycee Well #2 (P72663W) was installed to replace Kaycee No. 1 in July 1986.
Weston Engineering, Inc. (in association with Civil Engineering Professionals, Inc.), 2006, Town of Kaycee well and tank storage improvements level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Tensleep and Madison aquifers	Evaluation of existing water system, water demand, improvement alternatives with cost estimates, financing options, and permitting requirements.	New water supply well is not needed. Improvements to wells and storage tank recommended. Cost estimates and financing alternatives provided.	Kaycee obtains municipal water from two Madison aquifer wells, listed above.
Lance Creek				
Western Water Consultants, 1996, Lance Creek water supply master plan level I: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	White River and Inyan Kara Group aquifers	Evaluation of existing water system, water demand, improvement alternatives with cost estimates, financing options, and permitting requirements.	Storage, transmission, and distribution systems require additions and improvements with cost estimates provided.	Project completed.
WWC Engineering (in association with Wyoming Groundwater), 2011, Lance Creek water supply study level I, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	White River and Inyan Kara Group aquifers	Evaluation of existing water system, water demand, improvement alternatives with cost estimates, financing options, and permitting requirements.	Arsenic, radium and gross alpha levels are above the EPA MCL; new wells are needed.	Lance Creek Well Level II study was conducted (see next page).
Wyoming Groundwater, LLC (in association with WWC Engineering), 2013, Lance Creek well level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary and appendices are available under separate cover.*	White River Group, Inyan Kara Group, and Morrison Formations.	Described construction and testing of three test wells in the Inyan Kara aquifer to meet SDWA standards for arsenic, radium and gross alpha levels.	Water from State No. 2 Test Well meets SDWA standards for constituents of concern. Water from this well and the existing State No. 2 Well can be blended and still meet SDWA standards.	District is negotiating terms of use with the State for new well.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Little Goose				
Howard, Needles, Tammen, and Bergendoff (in association with Anderson and Kelly), 1987, Little Goose domestic water supply project study level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. *Executive summary is available under separate cover.*	Madison, Bighorn, Gallatin, Gros Ventre, and Flathead	Feasibility study of development of central water system to meet domestic requirements of Little Goose Valley. Evaluate potential of Little Goose Creek Well.	User costs of improving/installing one or two wells are excessive. Recommend studying feasibility of connection to Sheridan Water Supply system.	Most of the Little Goose Valley is outside of the SAWS service area. No record of PWS in EPA databases. Little Goose Well (P70444.0W) permit cancelled in 2012, refiled as P199097.0W in 2012.
Lusk				
Worthington, Lenhart, Carpenter, Inc., 1994, Town of Lusk water project level I master plan study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Arikaree	Evaluation of existing water system, water demand, improvement alternatives with cost estimates, financing options, and permitting requirements.	Improve water storage and delivery infrastructure. Drill a new test well near the airport and evaluate its potential to supplement water supplies from Well #8. Abandon existing Wells #3 and #4.	Project completed.
MK Centennial, 1995, Lusk water supply project level II - Lusk, Wyoming, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Arikaree	Evaluation of improvement alternatives proposed in Level I (see previous). Description of installation of new well (Lusk #9). Analysis of maintenance and operating cost.	Recommend improvements in water delivery and storage system in conjunction with construction of Well #9.	Project completed.
TriHydro Corporation, 1996, Well construction and aquifer testing level II water supply project, Lusk, Wyoming final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Arikaree	Drilling, construction, development, and testing report of Lusk #9 Well.	Well #9 produces 800 gpm of good-quality water suitable for municipal use. Town should consider developing a well field around Well #9.	Project completed.
Hinckley Consulting (in association with Wyoming Groundwater), 2009, Lusk area groundwater level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Arikaree with a hydrostratigraphic survey of other area geologic units	Evaluation of area geologic formations for groundwater resource potential.	Arikaree aquifer is only hydrostratigraphic unit with groundwater development potential.	Project completed.
AVI Professional Corporation (in association with TST and Hinckley Consulting), 2014, Lusk master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Arikaree	Evaluation of existing water system, water demand, improvement alternatives with cost estimates, financing options, and permitting requirements.	Recommendations to improve groundwater pumping, storage, and delivery systems. Town should consider replacing Well #1 and installing new well at site of old Well #3.	At the time of this report, WWDC was conducting a Lusk Level II Water Supply Study.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Manville				
Western Water Consultants, 1997, Final report on the Manville water supply project level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. Executive summary is available under separate cover.	Arikaree	Evaluation of Manville's water supply, condition of wells, and municipal water infrastructure. Prepare improvement alternatives, cost estimates, and financing options.	Manville Well #3 was drilled, completed, developed, and tested. Recommended improvements to water delivery system.	Project completed.
Olsson Associates (in association with AVI), 2008, Manville source water supply study level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Arikaree	Evaluate options to bring water supply into compliance with EPA regulations. Prepare improvement alternatives with cost estimates.	Examined treatment and water source replacement options. Recommended replacing worn water delivery infrastructure.	Project completed.
Wyoming Groundwater, LLC (in association with Gordon Marlatt, Ph.D. and WWC Engineering), 2014, Manville well level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Hartville and Arikaree aquifers	Evaluate water production and quality of the Hartville and Arikaree aquifers. Drill, install, complete, and test new well. Design infrastructure to connect to new well. Estimate costs of water supply improvement project.	Manville #4 test well was drilled and installed in Arikaree aquifer. Well produces 250 gpm of good-quality water.	At the time of this report, WWDC was conducting a Manville Level III Water Supply construction project.
Middle Fork of the Powder River				
Wright Water Engineers, Inc. (in association with Worthington, Lenhart, Carpenter, and Johnson, Inc.), 1984, Middle Fork Rural Water District domestic water system level I, reconnaissance study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Tensleep and Madison aquifers	Evaluate groundwater and surface water sources for the Middle Fork Rural Water District. Prepare cost estimates and an operating plan for water system improvements.	Cost analysis indicates the groundwater wells at the Red Fork of the Powder River site provide most cost effective option for supplying water to the water district.	Project completed.
TriHydro Corporation, 1985, Level II exploratory drilling program for the Middle Fork Rural Water District: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Amsden, Tensleep, and Madison aquifers	Drill, complete, test, and construct groundwater well in the Madison aquifer.	Test well, installed in Madison aquifer, produced up to 800 gpm of poor-quality water. Recommend long-term flow test and water treatment study.	Current status unknown. Middle Fork #1 permit (P70450.0W) was cancelled and then refiled under permit P102065.0W. No current record of Middle Fork Rural Water District.
Moorcroft				
Weston Engineering, Inc., 1991, Moorcroft water study level I: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Lance, Fox Hills, and Madison aquifers	Evaluation of Moorcroft's water supply, storage and distribution system, water requirements, and water supply alternatives.	Conduct economic analysis (Level II) of upgrading town's water supply infrastructure and obtaining new source(s) of municipal water.	Project completed.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Moorcroft (cont.)				
Weston Engineering, Inc., 1992, Moorcroft water study level I: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Lance, Fox Hills, and Madison aquifers	Economic analysis of previous study to include water supply alternatives, cost estimates, and financing.	Alternatives included construction of water storage reservoir, new well in Lance-Foxhills aquifer, and collection system to existing municipal wells.	Project completed.
Bearlodge Ltd, Inc. (in association with J.P. Gries, P.G. and Soda Butte Services), 1994, Moorcroft water study level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Lance-Fox Hills aquifer system	Reports on construction and testing of Lance-Fox Hills test well, and design and cost estimates of storage and delivery improvements suggested in Weston Engineering (1992).	New well provides sufficient quantity of good-quality water. Study recommends that town and WWDC proceed with funding and construction of planned storage and delivery infrastructure.	Project completed.
Weston Engineering, Inc., 2002, Moorcroft water study level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison	Evaluate present/future water needs, water supply alternatives, and groundwater resources, and inventory existing water supply facilities, Prepare improvement alternatives and cost estimates.	New Madison exploration well provides sufficient quantity of good-quality water. Recommend that the municipal water system connect to the new well.	Project completed.
HDR Engineering, Inc. (in association with Western Groundwater Services, LLC.), 2015, Town of Moorcroft master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Lance, Fox Hills, and Madison aquifers	Evaluate present/future water needs, existing water supply facilities and operations, water quality, and water rights. Develop hydraulic model. Prepare cost estimates and financing alternatives.	Implement a valve maintenance program and report water usage to SEO. Replace selected water mains and install a portable transmission loop.	Moorcroft obtains municipal water from one Madison aquifer and several Lance/ Fox Hills wells. Moorcroft also purchases water from the Gillette Regional Water System.
Newcastle				
RCH and Associates (in association with Wester-Wetstein and Associates), 1996, Level I water supply project, Salt Creek Water District, Newcastle, Wyoming, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Evaluate present/future water needs, existing water supply facilities, operations, and permitting. Develop hydraulic models. Prepare cost estimates and financing alternatives.	Connect facilities of West End Water District, City of Newcastle, and Salt Creek Water District systems to form area wide water system. Drill new Madison aquifer well.	Project completed.
Wester-Wetstein and Associates, Inc. (in association with States West Water Resources Corp.), 2000, Newcastle area water supply master plan, level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged].	Minnelusa and Madison aquifers	Evaluate Newcastle Area water supply delivery and storage systems. Includes West End Water District, City of Newcastle, Salt Creek Water District, and Cambria Water District systems.	Recommended infrastructure improvements made to each water system entity. Report provides a summary of Madison aquifer performance in Newcastle area.	Project completed.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Newcastle (cont.)				
Stetson Engineering, Inc. (in association with Western Groundwater Services, LLC.), 2005, Final level II study report for Canyon Improvement and Service District, Newcastle, Wyoming, includes Canyon No. 1 test well construction report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary and attachments are available under separate covers.*	Minnelusa and Madison aquifers	Evaluation of Canyon service area aquifers to meet community water demands. Canyon #1 Well drilled into Madison aquifer to TD of ~2,200 ft. Initial head was 100 PSI, max production estimated at 500 gpm.	Proceed with Level III funding to complete well and construct transmission and storage facilities. New well has potential to provide water to a regional system.	At the time of this report, WWDC was funding a Level II Newcastle Madison Well Study.
Osage				
Banner Associates, Inc. (in association with Arnjac Corp.), 1994, Osage water supply project level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Evaluate water supply, existing distribution and storage, and existing and future water demand. Analyze water supply alternatives.	Presents three alternatives that all include town purchase of the existing private water system, with infrastructure improvements supplemented by drilling one or two additional Madison wells.	Project completed.
Banner Associates, Inc. (in association with Soda Buttes Services, Inc.), 1996, Osage water supply project level II extension, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Engineering and financial evaluations of fourth alternative: acid stimulation of BHP&L Well #4 coupled with storage and delivery system improvements. Report of stimulation results.	Recommended improvements in existing delivery system and resolution of right-of-way and easement issues.	Osage Water District PWS obtains water from two Madison aquifer wells.
Pine Butte				
Centennial Engineering & Research, Inc., 1991, Level I reconnaissance information, Pine Butte Improvement and Service District, Gillette, Wyoming: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Wasatch, Fort Union, and Fox Hills aquifers	Evaluate water supply, existing distribution and storage, and existing and future water demand. Analyze water supply alternatives.	Due to the high costs of extending water supply lines from Gillette, Pine Butte should not be included in the Gillette Regional Water System, but should develop its own water supply.	Project completed.
HKM Engineering (in association with Soda Buttes Services, Inc.), 1992, Final report for a proposed water supply system for Pine Butte Improvement and Service District: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Wasatch, Fort Union, and Fox Hills aquifers	Design and estimate costs for a new community well completed in the Lower Fort Union aquifer.	Pine Butte should develop its own water supply by drilling a new community well completed in the Lower Fort Union aquifer. Nearby existing wells would supply the community in the interim.	Project completed.
Wester Wetstein & Associates, 1993, Construction, testing and conceptual completion design of the Pine Butte No. 1 well for the Pine Butte Water Supply Project level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Tullock Member of the Fort Union aquifer	Report of construction, testing, and conceptual completion design of the Pine Butte No. 1 Well.	New well produced adequate amounts of fair-quality groundwater, which exceeded EPA standards for radium, iron, and TDS. Water quality could be brought into compliance with treatment.	The Pine Butte Improvement and Service District declined to purchase the Pine Butte No 1 test well (P91808.0W) from WWDC. Permit was cancelled.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Pine Haven				
Stetson Engineering, Inc., 2000, Pine Haven master plan level I reconnaissance study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Evaluate present/future water needs, existing water supply facilities and operations, and permitting. Prepare system alternatives and cost estimates.	Recommendations to improve groundwater pumping, storage, and delivery systems. Town should consider installing new Madison well as a back-up source of supply.	Project completed.
Wester Wetstein & Associates, 2003, Pine Haven well project level II, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Report of construction and testing of the Pine Haven No. 2 Well and cost estimates for water delivery infrastructure, tying the new well to the town's water system.	New well produced adequate amounts of fair-quality groundwater, which exceeded EPA standards for sulfate, iron and TDS. Cost estimates for delivery system alternatives included.	Project completed.
Bearlodge Ltd, Inc. (in association with Tetra Tech, Inc.), 2009, Pine Haven master plan level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Evaluate present/future water needs, existing water supply facilities and operations, water quality, and permitting. Prepare system alternatives and cost estimates.	Recommended infrastructure improvements made to water storage and delivery systems. Supply wells are adequate until 2023.	Project completed.
Baker & Associates, Inc. (in association with Wyoming Groundwater, LLC), 2014, Pine Haven tank & well level II study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Madison aquifer	Evaluate present/future water needs, existing water supply facilities and operations, and permitting. Prepare system alternatives and cost estimates.	Recommended infrastructure improvements made to water storage and delivery systems. Drill and complete a new Madison aquifer well. Abandon Pine Haven #1 well and rehabilitate Pine Haven #2 Well.	Pine Haven project has not moved into Level III.
Powder River				
Harza Engineering Company, 1982, Storage developments for water supply, Powder River Basin in Wyoming, level I reconnaissance study, main report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. *Status report to Legislature and appendices are available under separate cover.*	Alluvial, Wasatch, Fort Union, and Madison aquifers	Surface water report that provides a brief evaluation of groundwater resources in the aquifers listed at left.	Groundwater resources in the interior PRB likely could serve only as an interim water supply.	Several communities in the PRB are supplied by groundwater.
Town of Powder River				
Banner Associates, Inc., 2002, Powder River water supply level I study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Quaternary alluvial aquifer	Evaluate present/future water needs, existing water supply facilities and operations, and permitting. Prepare system alternatives and cost estimates. Conduct groundwater exploration study.	Recommended that Powder River #1 Well (P107884.0W) be treated with reverse osmosis technology or that new water source be found. Quaternary alluvium aquifer is most economic supply alternative.	Businesses using Powder River #1 have closed. No PWS listed for town. Presumed that residents are served by individual domestic wells.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Prairie Dog Creek Watershed				
EnTech, Inc. (in association with Steady Stream Hydrology, Inc.), 2001, Final report for Prairie Dog Creek watershed master plan level I study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Alluvial and Wasatch aquifers	Surface water report that provides a brief evaluation of groundwater resources in the aquifers listed at left.	Form a watershed improvement district to address surface water issues. Groundwater resources are limited to individual domestic, stock, and agricultural wells.	Residents of Sheridan subdivisions located in the Prairie Dog Creek Watershed may be served by the Sheridan Area Water System SAWS). Others by individual wells.
Sheridan				
Western Water Consultants, Inc., 1982, Potential for groundwater development, City of Sheridan, Wyoming, [variously paged].	Lance-Fox Hills and Fort Union aquifers	Feasibility study to assess the potential for economic development of beneficial amounts of water for municipal use.	The Lance-Fox Hills and Fort Union Formation have variable characteristics and water quality. The economic feasibility of the groundwater supply can be better assessed after construction of a new test well.	See below.
Howard Needles Tammen and Bergendoff, 1985, Sheridan area water supply investigation, Level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. *Executive summary is available under separate cover.*	Paleozoic aquifers	Identify and evaluate alternative development programs to provide a dependable water supply for the Sheridan area through 2035. Determine water development potential of the Paleozoic aquifers west of Sheridan.	Evaluation of Little Goose Well and Big Goose Well, improvement alternatives and cost estimates. Water from Big and Little Goose wells meet primary and secondary drinking water standards.	The Sheridan Area Water System obtains its water from surface water sources.
Sleepy Hollow				
Brown and Caldwell, 2005, Drilling, construction, development, and testing of Sleepy Hollow Well No. 6: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Lance-Fox Hills and Fort Union aquifers	Report describes project where Sleepy Hollow Well #6 was drilled and tested.	Well was drilled by reverse-circulation drilling. Transmissivity of the well was estimated at 315 ft^2/day. WQ was deemed suitable for potable use and meets primary and secondary drinking-water standards for a public water system with disinfection.	Sleepy Hollow obtains its water from the project well (Well #6) and four others.
Sundance				
Bearlodge Ltd., Inc., 1986, Report for the Sundance groundwater project, Sundance No. 6 well: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Minnelusa and Pahasapa aquifers	Project provides data from the first drilling project into the Madison Formation in the Sundance area to find a new potential municipal source.	Water quality was well within EPA drinking water standards and a proposed "safe yield" for the well was recommended at 400 gpm.	See below.
TriHydro Corporation, 2013, Sundance master plan level I, Crook County, Wyoming, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary and appendices are available under separate cover.*	Minnelusa and Pahasapa aquifers	Identify solutions and alternatives for addressing water supply issues and concerns of the City of Sundance.	Generate a hydraulic model to use for master planning for water usage, transmission, and storage.	Project completed.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Sundance (cont.)				
TriHydro Corporation (in association with DOWL and DC Drilling), 2015, Sundance water system feasibility level II study, Crook County, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Minnelusa and Pahasapa aquifers	Review of Level I study recommendations and cost analysis. The Cole Well Field was evaluated to determine if the wells could be used for municipal water supply.	Complete a downhole video survey to assess condition of wells, replace the production piping in Cole Well 3A in 5-10 years. Additional well development in Cole Wells 3 and 3A may be necessary if sediment accumulation becomes an issue.	Sundance obtains municipal water from wells completed in Paleozoic aquifers.
Three Horses				
EnTech, Inc. (in association with Environmental Design Engineering and RIMCON, LLC), 2002, Three Horses watershed plan, Level I study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. Executive summary is available under separate cover.	Wasatch and Fort Union aquifers	Summarize characteristics of the watershed and evaluate potential CBM impacts and water management alternatives.	Current methods of addressing CBM water issues are best given present regulations. If proper precautions are taken, some CBM waters may be suitable for irrigation purposes.	Watershed study completed.
Thunder Basin				
Olsson Associates (in association with ESCO Associates, Inc., Wester-Wetstein Associates, and Steady Stream Hydrology, Inc.), 2009, Thunder Basin watershed management plan, level 1 watershed study, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. *Executive summary is available under separate cover.*	Alluvial, springs, Wasatch Formation, Fort Union Formation, Lance Formation (Lance-Fox Hills aquifer)	Describe Thunder Basin watershed in its current condition and make recommendations for issues/opportunities identified through this study. Contains groundwater registered well inventory map, groundwater registered yield map, and groundwater registered well depth map.	Dispersal of upland watering sources for livestock will reduce the pressure in current drainage ways where livestock currently water. Installation of shallow-moderately deep wells, solar powered pumps, stock tanks, piping, and fencing are recommended.	See below.
Olsson Associates (in association with ESCO Associates, Inc., Wester-Wetstein Associates, and Steady Stream Hydrology, Inc.), 2009, Thunder Basin Phase II watershed management plan, level I watershed study, Lance and Lightning Creek, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, 2 v., [variously paged]. Executive summary is available under separate cover.	Alluvial, springs, Arikaree Formation, Wasatch Formation, Fort Union Formation, Lance Formation	Describe current conditions of Lance Creek and Lightning Creek sub-basins and make recommendations for issues/ opportunities identified through this study. Contains groundwater registered well inventory map, groundwater registered yield map, and groundwater registered well depth map.	Groundwater is suitable for livestock/ wildlife watering and should be expanded in areas where watering opportunities are scarce.	Thunder Basin studies completed. Unknown if suggested improvements are being implemented.
Tongue-Little Bighorn River Basin				
Wyoming Water Development Commission, 1984, Water development potential in the Tongue River Basin, level I reconnaissance study: prepared by the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison, Lance-Fox Hills, Fort Union, Wasatch aquifers	Conduct a basin-wide development plan to provide municipal water to Sheridan and other communities in the Tongue River Basin.	Report provides a comprehensive summary of previous groundwater studies in the basin and a bibliography.	See below.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Tongue-Little Bighorn River Basin (cont.)				
Banner Associates, Inc., 1985, Tongue River level I, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged].	Madison aquifer	Investigate water availability and development potential in the Tongue River drainage.	Good-quality groundwater can be developed by constructing well fields at any of the three areas evaluated in this study.	Unknown if suggested improvements were implemented.
Upton				
Weston Engineering, Inc., 1991, Upton water supply project, level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Stimulate one of three wells serving the town of Upton to potentially enhance water supply to the community.	Well stimulation was successful and improved specific capacity of the well was improved by more than two-fold.	See below.
McLaughlin Water Engineers, Ltd, 2008, Upton Well No. 6 level II study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Investigation of contamination in Upton Well #6 which has prevented use of the well since its completion.	Contamination is due to the presence of iron fixing bacteria on the well casing and introduction of contaminants during well development. Well rehabilitation program and subsequent construction of delivery and storage systems recommended.	Upton currently draws water from Wells #2, #4, #7 and #8 all in the Madison aquifer. Water from Well #6 has been used for non-potable applications.
Vista West				
Baker and Associates, 1991, Vista West water supply project, level I study: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Madison aquifer	Find an alternative source of water for the Vista West community and assess logistics and cost.	A new Madison Formation well has the best potential for a successful water supply.	See below.
Weston Engineering, Inc., 1994, Vista West water supply project, Level II: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fractured intrusive rocks and Deadwood aquifer	Investigate the potential for purchasing water from Sundance and/or explore water production potential of fractured intrusive rocks and sedimentary rocks.	Fractured intrusive rocks yield significant quantities of water, which meets EPA primary and secondary drinking water standards. Test wells were installed and evaluated.	Test wells were developed as municipal wells Vista West #1 (P91988.0W 1nd P9189.0W) and #2 and are in use presently.
Wright				
Anderson & Kelly, Inc., 1986, Wright groundwater supply project, level III, drilling and testing of RJ-4 well, operating plan and preconstruction report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Wasatch and Fort Union aquifers	Drilling, construction, development, and testing of municipal supply well RJ-4.	Water pumped from the RJ-4 well meets EPA primary drinking water standards. Water from the Fort Union Formation meets most EPA drinking water standards except for iron.	See next page.

Citation(s)	Aquifer/ Formation	Project description	Results/Recommendations	Current status
Wright (cont.)				
Stetson Engineering, Inc. (in association with Wester-Wetstein & Associates), 2009, Wright master plan, level I study final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Wasatch and Fort Union aquifers	Establish a water master plan for the Wright Water and Sewer District and make plans for expansion to meet increasing demand.	Water levels are declining in wells in the Wright area. It is recommended that future wells be separated by at least one mile to avoid interference between wells. Drill an additional well (RJ-7) in the Wright area to meet increasing need for water supply.	Project completed.
HDR, 2012 (in association with Western Groundwater Services), Wright Water and Sewer District water supply level II study, Well no. RJ-7, final report: prepared for the Wyoming Water Development Commission, Cheyenne, Wyoming, [variously paged]. *Executive summary is available under separate cover.*	Fort Union aquifer	Drilling, construction, development, and testing of municipal supply well RJ-7.	The RJ-7 well yields 300 gpm and has water quality similar to the other RJ-wells in the system.	Wright draws municipal water from five– active wells including RJ-4. EPA and SEO data suggest that RJ-7 is not yet in operation.

Appendix C

GIS dataset sources for figures and plates

Dataset	Presented in	Source
GEOLOGY		
Powder, Tongue, and Northeast river basins geology	Plate I, various figures	Modified from Stoeser, D.B., et al., 2007, and Love, J.D., Christiansen, A.C., 1985
Precambrian basement structure contour	Plate I	Modified from Blackstone, 1993
Precambrian basement faults	Plate I	Modified from Blackstone, 1993
Cross-section lines	Plate I	WSGS
Lineaments	Plate I	Cooley, M. E., 1986
Faults, Wyoming	Plate I, Plate II	Modified from Stoeser, D.B., et al., 2007, and Love, J.D., Christiansen, A.C., 1985
Faults, Montana	Plate I, Plate II	Modified from Stoeser, D.B., et al., 2007
Faults, South Dakota	Plate I, Plate II	Modified from Stoeser, D.B., et al., 2007
Hydrogeology (includes aquifer outcrop areas)	Plate II, Figures 6-1, 6-2, 6-3, 6-4, 6-5, 6-6, 6-7	Bartos, T., USGS, 2017
GROUNDWATER		
Aquifer recharge as a percent of precipitation	Figure 6-8	Taboga and Stafford, WSGS, 2016
Aquifer sensitivity	Figure 5-3	Hamerlinck and Arneson, 1998
Average annual precipitation, 1981–2010	Figure 3-3	PRISM Climate Group, Oregon State University
Estimated net annual aquifer recharge	Figure 5-2	Taboga and Stafford, WSGS, 2016
Springs		Stafford and Gracias, WSGS, 2009
SWAP locations	Figure 5-11	Modified from Trihydro Corporation, 2004
Permitted wells	Figures 8-1, 8-2, 8-3, 8-4, 8-5, 8-6, 8-7	Wyoming State Engineer's Office, 2015 Montana Groundwater Information Center, 2015 Nebraska Department of Natural Resources South Dakota Department of Environment and Natural Resources, 2015
POTENTIAL GROUNDWATER CONTAMINANTS		
Abandoned mine sites	Figure 5-7	Created from WDEQ Abandoned Mine Land table of 2016
Active coal mine	Figure 5-8	WDEQ, Land Quality Division, 2015
Active disposal and injection wells	Figure 5-5	Modified from WOGCC well header data as of 2016
Small, Limited, and Regular Mining Permits	Figure 5-8	WDEQ LQD, 2016
Non Coal Mines	Figure 5-8	WDEQ LQD, 2016
Storage tanks	Figure 5-10	Modified from WDEQ Solid and Hazardous Waste Division (SHWD) storage tank table of 2016
Active Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Figure 5-6	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2016
Commercial oil and gas disposal pits	Figure 5-10	WDEQ/WQD commercial oil and gas disposal pit GIS dataset of 2016
Pollution Control Facilities	Figure 5-6	WDEQ/WQD Groundwater Program known contaminated areas GIS dataset of 2016
Oil and gas fields	Figure 5-4	Toner et al. 2016

Dataset	Presented in	Source
Pipelines	Figure 5-4	Wyoming Pipeline Authority 2016
Solid and hazardous waste facilities	Figure 5-10	Modified from WDEQ SHWD solid and hazardous waste facilities table of 2016
Underground Injection Control (UIC) Class I and V wells	Figure 5-5	Modified from WDEQ/WQD UIC GIS dataset of 2016
Voluntary Remediation Program (VRP) sites	Figure 5-10	Modified from WDEQ SHWD VRP tables and GIS datasets of 2016
WSGS mines, pits, mills, and plants	Figure 5-9	Harris, 2004
	BASE DATA	
Basin boundary	Plate I, various figures	Modified from USGS National Hydrography Dataset hydrologic units
Elevation	Plate I, various figures	Modified from USGS, 1999
Hillshade	Plate I, various figures	USGS, 1999
Lakes	Plate I, various figures	USGS, National Hydrologic Dataset
Rivers	Plate I, various figures	USGS, National Hydrologic Dataset
State boundaries	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming, Monatana, South Dakota, and Nebraska counties	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming, Monatana, South Dakota, and Nebraska townships	Plate I, various figures	Premier Data Services, 2008
Mountain peaks	Physiographic features figure	WSGS, unpublished mountain peaks GIS dataset of 2008
Roads	Plate I, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Places (cities, towns, etc.)	Plate I, various figures	Modified from USGS - Geographic Names Information System 2015

Appendix D

Interstate River Compacts of the Northeast River Basins

BELLE FOURCHE RIVER COMPACT, 1943

Signatory States: South Dakota and Wyoming

Rivers Controlled: Belle Fourche River and its tributaries arising in Wyoming.

Ratifications: Wyo. Stat. Ann. §4l-12-201 through 215 (2005) [Act of March 3, 1943, 1943 Wyo. Sess. Laws, ch. 117, p. 153]

S.D. Codified Laws §46A-17-l (2005) [Act of March 4, 1943, 1943 S.D. Sess. Laws ch. 283, p. 281]

Summary: This Compact recognizes all existing rights in Wyoming, as of the date of the Compact. It permits Wyoming unlimited use for stock water reservoirs not exceeding 20 acre-feet in capacity, and it allows Wyoming to deplete the unappropriated flow under the conditions existing as of the date of the compact by an additional 10%.

BELLE FOURCHE RIVER COMPACT, 1943

The States of South Dakota and Wyoming, parties signatory to this Compact (hereinafter referred to as South Dakota and Wyoming, respectively, or individually as a State, or collectively as the States) have resolved to conclude a compact as authorized under the Act of Congress of February 26, 1927, Chapter 216, 44 Stat. 1247, and, after negotiations participated in by the following named State Commissioners.

For South Dakota:	M. Q. SHARPE G. W. MORSMAN S. G. MORTIMER W. D. BUCHHOLZ
For Wyoming:	L. C. BISHOP SAMUEL McKEAN L. H. ROBINSON Mrs. E. E. McKEAN

and by Howard R. Stinson, appointed as the Representative of the United States of America, have agreed upon the following articles, to-wit:

ARTICLE I

A. The major purposes of this compact are to provide for the most efficient use of the waters of the Belle Fourche River Basin (hereinafter referred to as the Basin) for multiple purposes; to provide for an equitable division of such waters; to remove all causes, present and future, which might lead to controversies; to promote interstate comity; to recognize that the most efficient utilization of the waters within the basin is required for the full development of the basin; and to promote joint action by the states and the United States in the efficient use of water and the control of floods.

B. The physical and other conditions peculiar to the Basin constitute the basis for this compact; and none of the States hereby, nor the Congress of the United States by its consent, concedes that this compact establishes any general principle or precedent with respect to any other interstate stream.

C. Either State and all others using, claiming or in any manner asserting any right to the use of the waters of the Belle Fourche River under the authority of that State, shall be subject to the terms of this Compact.

ARTICLE II

As used in this Compact:

A. The term "Belle Fourche River" shall mean and include the Belle Fourche River and all its tributaries originating in Wyoming

B. The term "basin" shall mean that area in South Dakota and Wyoming, which is naturally drained by the Belle Fourche River, and all its tributaries

C. The term “beneficial use” is herein defined to be that use by which the water supply of a drainage basin is depleted when usefully employed by the activities of man, and includes water lost by evaporation, and other natural causes from streams, canals, ditches, irrigated areas, and reservoirs;

D. Where the name of the State or the term “State” or “States” is used, these shall be construed to include any person or entity of any nature whatsoever using, claiming, or in any manner asserting any right to the use of the waters of the Belle Fourche River under the authority of that State.

ARTICLE III

It shall be the duty of the two States to administer this Compact through the official in each State who is now or may hereafter be charged with the duty of administering the public water supplies, and to collect and correlate through such officials the data necessary for the proper administration of the provisions of this Compact. Such officials may, by unanimous action, adopt rules and regulations consistent with the provisions of this Compact.

The United States Geological Survey, or whatever federal agency may succeed to the functions and duties of that agency, insofar as this Compact is concerned, shall collaborate with the officials of the States charged with the administration of this Compact in the execution of the duty of such officials in the collection, correlation, and publication of information necessary for the proper administration of this Compact.

ARTICLE IV

Each State shall itself or in conjunction with other responsible agencies cause to be established, maintained, and operated such suitable water gaging stations as it finds necessary to administer this Compact.

ARTICLE V

A. Wyoming and South Dakota agree that the unappropriated waters of the Belle Fourche River as of the date of this Compact shall be allocated to each State as follows:

90% to South Dakota

10% to Wyoming;

Provided, that allocations to Wyoming shall be exclusive of the use of these waters for domestic and stock use, and Wyoming shall be allowed unrestricted use for these purposes, except that no reservoir for such use shall exceed twenty (20) acre-feet in capacity. For storage of its allocated water, Wyoming shall have the privilege of purchasing at cost not to exceed ten percent (10%) of the total storage capacity for any reservoir or reservoirs constructed in Wyoming for irrigation of lands in South Dakota, or may construct reservoirs itself for the purpose of utilizing such water. Either State may temporarily divert, or store for beneficial use, any unused part of the above percentages allotted to the other, but no continuing right shall be established thereby.

B. Rights to the use of the waters of the Belle Fourche River, whether based on direct diversion or storage, are hereby recognized as of the date of this Compact to the extent these rights are valid under the law of the State in which the use is made, and shall remain unimpaired hereby. These rights, together with the additional allocations made under A of this Article, are agreed to be an equitable apportionment between the States of the waters of the Basin.

C. The waters allocated under A of this Article and the rights recognized under B of this Article are hereinafter referred to collectively as the apportioned water. For the purposes of the administration of this Compact and determining the apportioned water at any given date within a given calendar year, there shall be taken the sum of:

(1) The quantity of water in acre-feet that passed the Wyoming-South Dakota state line during the period from January 1 of that year to that given date

(2) The quantity of water in acre-feet in storage on that date in all reservoirs built in Wyoming on the Belle Fourche River subsequent to the date of this Compact.

ARTICLE VI

Any person, entity, or State shall have the right to acquire necessary property rights in another State by purchase or through the exercise of the power of eminent domain for the construction, operation and maintenance of storage reservoirs and of appurtenant works, canals, and conduits required for the enjoyment of the privileges granted by Article V and Article VII A; provided, however, that the grantees of such rights shall pay to the political subdivisions of the State in which such works are located, each and every year during which such rights are enjoyed for such purposes, a sum of money equivalent to the average annual amount of taxes assessed against the lands and improvements thereon during the 10 years preceding the use of such lands in reimbursement for the loss of taxes to said political subdivisions of the State.

ARTICLE VII

A. Either State shall have the right, by compliance with the laws of the other State, to file applications for and receive permits to construct or participate in the construction and use of any dam, storage reservoir, or diversion works in such State for the purpose of conserving and regulating the apportioned water of the other State; provided, that such right is subject to the rights of the other State to control, regulate, and use water apportioned to it.

B. Each claim hereafter initiated for storage or diversion of water in one State for use in another State shall be filed in the Office of the State Engineer of the State in which the water is to be stored or diverted, and a duplicate copy of the application including a map showing the character and location of the proposed facilities and the lands to be irrigated shall be filed in the Office of the State Engineer of the State in which the water is to be used. If a portion or all the lands proposed to be reclaimed are located in a State other than the one in which the water is to be restored or diverted, then, before approval of the application shall be granted, said application shall be checked against the records of the appropriate office of the State in which the water is to be used, and a notation shall be placed thereon by the officer in charge of such records to the effect that the land description does not indicate a conflict with existing water rights. All endorsements shall be placed on both the original and duplicate copies of all such maps filed to the end that the records in both States may be complete and identical.

C. Appropriations may hereafter be adjudicated in the State in which the water is stored or diverted, and where a portion or all the lands irrigated are in the other State, such adjudications shall be confirmed in the latter State by the proper authority. Each adjudication is to conform with the laws of the State where the water is stored or diverted and shall be recorded in the county and State where the water is used.

ARTICLE VIII

In case any reservoir is constructed in, Wyoming to be used principally for irrigation of lands in South Dakota, sufficient water not to exceed 10 cubic feet per second shall be released at all times for stock water use.

ARTICLE IX

No reservoir hereafter built solely to utilize the water allocated to Wyoming shall have a capacity in excess of one thousand (1,000) acre-feet.

ARTICLE X

The provisions of this Compact shall remain in full force and effect until amended by action of the legislature of the States and consented to and approved by the Congress of the United States in the same manner as this Compact is required to be ratified to become effective.

ARTICLE XI

This Compact may be terminated at any time by unanimous consent of the States, and upon such termination, all rights then established hereunder or recognized hereby shall continue to be recognized as valid by the States notwithstanding the termination of the other provisions of the Compact.

ARTICLE XII

Nothing in this Compact shall be construed to limit or prevent either state from instituting maintaining any action or proceeding, legal or equitable, in any federal court or the United States Supreme Court for the protection of any right under this Compact or the enforcement of any of its provisions.

ARTICLE XIII

Nothing in this Compact shall be deemed:

A. To impair or affect any rights or powers of the United States, its agencies, or instrumentalities, in and to the use of the waters of the Belle Fourche River nor its capacity to acquire rights in and to the use of said waters

B. To subject any property of the United States, its agencies, or instrumentalities to taxation by either State or subdivision thereof, or to create an obligation on the part of the United States, its agencies, or instrumentalities, by reason of the acquisition, construction or operation of any property or works of whatsoever kind, to make any payments to any State or political subdivision thereof, State agency, municipality, or entity whatsoever in reimbursement for the loss of taxes;

C. To subject any property of the United States, its agencies, or instrumentalities, to the laws of any State to an extent other than the extent to which these laws would apply without regard to the Compact.

ARTICLE XIV

This Compact shall become operative when approved by the legislature of each of the States, and when consented to by the Congress of the United States by legislation providing, among other things, that:

A. Any beneficial uses hereafter made by the United States, or those acting by or under its authority, within a State, of the waters allocated by this Compact, shall be within the allocations hereinabove made for use in that State and shall be taken into account in determining the extent of use within that State;

B. The United States, or those acting by or under its authority, in the exercise of rights or powers arising from whatever jurisdiction the United States has in, over and to the waters of the Belle Fourche River and all its tributaries, shall recognize, to the extent consistent with the best utilization of the waters for multiple purposes, that beneficial use of the waters within the basin is of paramount importance to development of the Basin, and no exercise of such power or right thereby that would interfere with the full beneficial use of the waters shall be made except upon a determination, giving due consideration to the objectives of this Compact and after consultation with all interested federal agencies and the State officials charged with the administration of this Compact, that such exercise is in the interest of the best utilization of such waters for multiple purposes;

C. The United States, or those acting by or under its authority, will recognize any established use, for domestic and irrigation purposes, of the apportioned waters which may be impaired by the exercise of Federal jurisdiction in, over, and to such waters; provided, that such use is being exercised beneficially, is valid under the laws of the appropriate State and in conformity with this Compact at the time of the impairment thereof, and was validly initiated under State law prior to the initiation or authorization of the federal program or project which causes such impairment.

ARTICLE XV

Should a court of competent jurisdiction hold any part of this Compact to be contrary to the constitution of any State or of the United States, all other severable provisions shall continue in full force and effect.

IN WITNESS WHEREOF, the Commissioners have signed this Compact in triplicate original, one of which shall be filed in the archives of the Department of State of the United States of America and shall be deemed the authoritative original, and of which a duly certified copy shall be forwarded to the Governor of each of the States.

Done at the City of Cheyenne in the State of Wyoming, this 18th day of February, in the year of Our Lord, One Thousand Nine Hundred and Forty-Three.

Commissioners for South Dakota:	M. Q. SHARPE G. W. MORSMAN S. G. MORTIMER W. D. BUCHHOLZ
Commissioners for Wyoming:	L. C. BISHOP SAMUEL McKEAN L. H. ROBINSON Mrs. E. E. McKEAN

I have participated in the negotiation of this Compact and intend to report favorably thereon to the Congress of the United States.

HOWARD R. STINSON

Representative of the United States of America

NOTES

Congressional Consent to Negotiations. --- By the Act of February 26, 1927 (44 Stat. 1247), the Congress gave its consent to the negotiation by the States of South Dakota and Wyoming of compacts "providing for an equitable division and apportionment * * * of the water supply of the Belle Fourche" and other streams common to the two States. This consent was given "upon condition that a representative of the United States from the Department of the Interior, to be appointed by the President, shall participate in the negotiations and shall make report to Congress of the proceedings and of any compact or agreement entered into." It was also provided that no such compact or agreement should become effective until it had been "approved" by the legislatures of the States and by Congress.

Congressional Consent to the Compact. --- Act of February 26, 1944 (58 Stat. 94) from which the text of the Compact above is taken.

Section 2 of this Act reads as follows:

"(a) In order that the conditions stated in Article XIV of the Compact hereby consented to shall be met and that the Compact shall be and continue to be operative, the following provisions are enacted:

"(1) Any beneficial uses hereafter made by the United States, or those acting by or under its authority, within a State, of the waters allocated by such compact, shall be within the allocations made by such compact for use in that State and shall be taken into account in determining the extent of use within that State;

"(2) The United States, or those acting by or under its authority, in the exercise of rights or powers arising from whatever jurisdiction the United States has in, over, and to the waters of the Belle Fourche River and all its tributaries shall recognize, to the extent consistent with the best utilization of the waters for multiple purposes, that beneficial use of the waters within the Basin is of paramount importance to the development of the Basin; and no exercise of such power or right thereby that would interfere with the full beneficial use of the waters within the Basin shall be made except upon a determination, giving due consideration to the objectives of such compact and after consultation with all interested

Federal agencies and the State officials charged with the administration of such compact, that such exercise is in the interest of the best utilization of such waters for multiple purposes;

"(3) The United States, or those acting by or under its authority, will recognize any established use, for domestic and irrigation purposes, of the apportioned water which may be impaired by the exercise of Federal jurisdiction in, over, and to such water; Provided, That such use is being exercised beneficially, is valid under the laws of the appropriate State and in conformity with such compact at the time of the impairment thereof and was validly initiated under State law prior to the initiation or authorization of the Federal program or project which causes such impairment.

"(b) as used in this section, the following terms: 'beneficial use,' 'Basin,' and 'apportioned water,' shall have the same meanings as those ascribed to them in the compact consented to by this Act."

After approving the bill, the President issued the following statement dated February 28, 1944:

"In signing the Belle Fourche River Basin Compact bill, I find it necessary to call attention, as I did last May in the case of the Republican River Compact bill, to the restrictions imposed upon the use of water by the United States. The procedure prescribed by the bill for the exercise of the powers of the Federal Government would not be entirely satisfactory in all circumstances but the prospects in fact for the exercise of such powers in the Belle Fourche basin are not great. For streams where conditions are otherwise and there appears to be a possible need for Federal comprehensive multiple-purpose development or where opportunities for important electric power projects are present, I believe the Belle Fourche River Compact should not serve as a precedent. In such cases the compact and the legislation should more adequately reflect recognition of the responsibilities and prerogatives of the Federal Government."

Legislative History of the Compact. --- See H. R. 2580 and S. 1057, 78th Congress; House Report 788 (Committee on Irrigation and Reclamation) and Senate Report 683 (Committee on Irrigation and Reclamation), 78th Congress; 89 Cong. Rec. 9533-9535 *(1943),* 90 Cong. Rec. 1660 (1944) P. L. 236, 78th Congress. Hearings on H. R. 2580 were printed; for report of Federal representative see pp. 12-15.

YELLOWSTONE RIVER COMPACT, 1950

Signatory States: Montana, North Dakota and Wyoming

Rivers Controlled: Yellowstone River and its tributaries (Clarks Fork, Big Horn, Tongue and Powder), excluding Yellowstone National Park.

Ratifications: Wyo. Stat. Ann. §4l-12-601 (2005) [Act of Jan. 27, 1951, 1951 Wyo. Sess. Laws, ch. 10, p. 7]

Mont. Code Ann. §85-20-101 (2003) [Act of Feb. 13, 1951, 1951 Mont. Laws, ch. 39, p. 58]

N.D. Cent. Code §61-23-01 (2003) [Act of March 7, 1951, 1951 N.D. Laws, ch. 339, p. 505]

Summary: The Compact deals with division of the waters of the four tributaries to the Yellowstone River. To all tributaries the following rules apply: 1) existing rights as of January 1, 1950 maintain their status quo; 2) no water may be diverted from the Yellowstone River Basin without consent from all States; 3) existing and future domestic and stock water uses including stock water reservoirs up to a capacity of 20 acre-feet are exempted from provisions of the Compact.

The unappropriated or unused total divertable flow of each tributary after needs for supplemental supply for existing rights are met, is allocated to Wyoming and Montana on a percentage basis.

YELLOWSTONE RIVER COMPACT, 1950

The State of Montana, the State of North Dakota, and the State of Wyoming, being moved by consideration of interstate comity, and desiring to remove all causes of present and future controversy between said States and between persons in one and persons in another with respect to the waters of the Yellowstone River and its tributaries, other than waters within or waters which contribute to the flow of streams within the Yellowstone National Park, and desiring to provide for an equitable division and apportionment of such waters, and to encourage the beneficial development and use thereof, acknowledging that in future projects or programs for the regulation, control and use of water in the Yellowstone River basin the great importance of water for irrigation in the signatory States shall be recognized, have resolved to conclude a Compact as authorized under the Act of Congress of the United States of America, approved June 2, 1949 (Public Law 83, 81st congress, first session), for the attainment of these purposes, and to that end, through their respective governments, have named as their respective Commissioners:

For the State of Montana:

Fred E. Buck
A. W. Bradshaw
H. W. Bunston
John Herzog
John M. Jarussi
Ashton Jones
Chris Josephson
A. Wallace Kingsbury
P. F. Leonard
Walter M. McLaughlin
Dave M. Manning
Joseph Muggli
Chester E. Onstad
Ed F. Parriott
R. R. Renne
Keith W. Trout

For the State of North Dakota:

I. A. Acker
J. J. Walsh
Einar H. Dahl

For the State of Wyoming:

L. C. Bishop
Earl T. Bower
J. Harold Cash
Ben F. Cochrane
Ernest J. Goppert
Richard L. Greene
E. C. Gwillim
E. J. Johnson
Lee E. Keith
N. V. Kurtz
Harry L. Littlefield
R. E. McNally
Will G. Metz
Mark N. Partridge
Alonzo R. Shreve
Charles M. Smith
Leonard F. Thornton
M. B. Walker

who, after negotiations participated in by R. J. Newell, appointed as the representative of the United States of America, have agreed upon the following articles, to-wit:

ARTICLE I

A. Where the name of a State is used in this Compact, as a party thereto, it shall be construed to include the individuals, corporations, partnerships, associations, districts, administrative departments, bureaus, political subdivisions, agencies, persons, permittees, appropriators, and all others using, claiming, or in any manner asserting any right to the use of the waters of the Yellowstone River System under the authority of said State.

B. Any individual, corporation, partnership, association, district, administrative department, bureau, political subdivision, agency, person, permittee, or appropriator authorized by or under the laws of a signatory State, and all others using, claiming, or in any manner asserting any right to the use of the waters of the Yellowstone River System under the authority of said State, shall be subject to the terms of this Compact. Where the singular is used in this article, it shall be construed to include the plural.

ARTICLE II

A. The State of Montana, the State of North Dakota, and the State of Wyoming are hereinafter designated as "Montana", "North Dakota", and "Wyoming", respectively.

B. The terms "Commission" and "Yellowstone River Compact Commission" mean the agency created as provided herein for the administration of this Compact.

C. The term "Yellowstone River Basin" means areas in Wyoming, Montana, and North Dakota drained by the Yellowstone River and its tributaries, and includes the area in Montana known as Lake Basin, but excludes those lands lying within Yellowstone National Park.

D. The term "Yellowstone River System" means the Yellowstone River and all of its tributaries, including springs and swamps, from their sources to the mouth of the Yellowstone River near Buford, North Dakota, except those portions thereof, which are within or contribute to the flow of streams within the Yellowstone National Park.

E. The term "tributary" means any stream, which in a natural state contributes to the flow of the Yellowstone River, including interstate tributaries and tributaries thereof, but excluding those, which are within or contribute to the flow of streams within the Yellowstone National Park.

F. The term "interstate tributaries" means the Clarks Fork, Yellowstone River; the Bighorn River (except Little Bighorn River); the Tongue River; and the Powder River, whose confluences with the Yellowstone River are respectively at or near the city (or town) of Laurel, Big Horn, Miles City, and Terry, all in the State of Montana.

G. The terms "divert" and "diversion" means the taking or removing of water from the Yellowstone River or any tributary thereof when the water so taken or removed is not returned directly into the channel of the Yellowstone River or of the tributary from which it is taken.

H. The term "beneficial use" is herein defined to be that use by which the water supply of a drainage basin is depleted when usefully employed by the activities of man.

I. The term "domestic use" shall mean the use of water by an individual, or by a family unit or household for drinking, cooking, laundering, sanitation and other personal comforts and necessities; and for the irrigation of a family garden or orchard not exceeding one-half acre in area.

J. The term "stock water use" shall mean the use of water for livestock and poultry.

ARTICLE III

A. It is considered that no Commission or administrative body is necessary to administer this Compact or divide the waters of the Yellowstone River Basin as between the states of Montana and North Dakota. The provisions of this Compact, as between the States of Wyoming and Montana, shall be administered by a Commission composed of one representative from the State of Wyoming and one representative from the State of Montana, to be selected by the Governors of said States as such States may choose, and one representative selected by the Director of the United States Geological Survey or whatever Federal agency may succeed to the functions and duties of that agency, to be appointed by him at the request of the States to sit with the Commission and who shall, when present, act as Chairman of the Commission without vote, except as herein provided.

B. The salaries and necessary expenses of each State representative shall be paid by the respective State; all other expenses incident to the administration of this Compact not borne by the United States shall be allocated to and borne one-half by the State of Wyoming and one-half by the State of Montana.

C. In addition to other powers and duties herein conferred upon the Commission and the members thereof, the jurisdiction of the Commission shall include the collection, correlation, and presentation of factual data, the maintenance of records having a bearing upon the administration of this Compact, and recommendations to such States upon matters connected with the administration of this Compact, and the Commission may employ such services and make such expenditures as reasonable and necessary within the limit of funds provided for that purpose by the respective States, and shall compile a report for each year ending September 30 and transmit it to the Governors of the signatory States on or before December 31 of each year.

D. The Secretary of the Army; the Secretary of the Interior; the Secretary of Agriculture; the Chairman, Federal Power Commission; the Secretary of Commerce, or comparable officers of whatever Federal agencies may succeed to the functions and duties of these agencies, and such other federal officers and officers of appropriate agencies of the signatory states having services or data useful or necessary to the Compact Commission, shall cooperate, ex officio, with the Commission in the execution of its duty in the collection, correlation, and publication of records and data necessary for the proper administration of the Compact; and these officers may perform such other services related to the Compact as may be mutually agreed upon with the Commission.

E. The Commission shall have power to formulate rules and regulations and to perform any act which they may find necessary to carry out the provisions of this Compact, and to amend such rules and regulations. All such rules and regulations shall be filed in the office of the State Engineer of each of the signatory States for public inspection.

F. In case of the failure of the representatives of Wyoming and Montana to unanimously agree on any matter necessary to the proper administration of this Compact, then the member selected by the director of the United States Geological Survey shall have the right to vote upon the matters in disagreement and such points of disagreement shall then be decided by a majority vote of the representatives of the States of Wyoming and Montana and said member selected by the Director of the United States Geological Survey, each being entitled to one vote.

G. The Commission herein authorized shall have power to sue and be sued in its official capacity in any Federal Court of the signatory States, and may adopt and use an official seal, which shall be judicially noticed.

ARTICLE IV

The Commission shall itself, or in conjunction with other responsible agencies, cause to be established, maintained, and operated such suitable water gaging and evaporation stations as it finds necessary in connection with its duties.

ARTICLE V

A. Appropriative rights to the beneficial uses of the water of the Yellowstone River system existing in each signatory State as of January 1, 1950, shall continue to be enjoyed in accordance with the laws governing the acquisition and use of water under the doctrine of appropriation.

B. Of the unused and unappropriated waters of the interstate tributaries of the Yellowstone River as of January 1, 1950, there is allocated to each signatory State such quantity of that water as shall be necessary to provide supplemental water supplies for the rights described in paragraph (a) of this Article V, such supplemental rights to be acquired and enjoyed in accordance with the laws governing the acquisition and use of water under the doctrine of appropriation, and the remainder of the unused and unappropriated water is allocated to each State for storage or direct diversions for beneficial use on new lands or for other purposes as follows:

1. Clarks Fork, Yellowstone River

    a) To Wyoming 60%

    To Montana 40%

    b) The point of measurement shall be below the last diversion from Clarks Fork above Rock Creek.

2. Bighorn River (Exclusive of Little Bighorn River)

    a) To Wyoming 80%

    To Montana................ 20%

    b) The point of measurement shall be below the last diversion from the Bighorn River above its junction with the Yellowstone River, and the inflow of the Little Bighorn River shall be excluded from the quantity of water subject to allocation.

3. Tongue River

    a) To Wyoming 40%

    To Montana 60%

    b) The point of measurement shall be below the last diversion from the Tongue River above its junction with the Yellowstone River.

4. Powder River (Including the Little Powder River)

    (a) To Wyoming 42%

    To Montana 58%

    (b) The point of measurement shall be below the last diversion from the Powder River above its junction with the Yellowstone River.

C. The quantity of water subject to the percentage allocations, in Paragraph B 1, 2, 3 and 4 of this Article V, shall be determined on an annual water year basis measured from October 1st of any year through September 30th of the succeeding year. The quantity to which the percentage factors shall be applied through a given date in any water year shall be, in acre-feet, equal to the algebraic sum of:

1. The total diversions, in acre-feet, above the point of measurement, for irrigation, municipal, and industrial uses in Wyoming and Montana developed after January 1, 1950, during the period from October 1st to that given date;

2. The net change in storage, in acre-feet, in all reservoirs in Wyoming and Montana above the point of measurement completed subsequent to January 1, 1950, during the period from October 1st to that given date;

3. The net change in storage, in acre-feet, in existing reservoirs in Wyoming and Montana above the point of measurement, which is used for irrigation, municipal, and industrial purposes developed after January 1, 1950, during the period October 1st to that given date;

4. The quantity of water, in acre-feet, that passed the point of measurement in the stream during the period from October 1st to that given date.

D. All existing rights to the beneficial use of waters of the Yellowstone River in the States of Montana and North Dakota, below Intake, Montana, valid under the laws of these States as of January 1, 1950, are hereby recognized and shall be and remain unimpaired by this Compact. During the period May 1 to September 30, inclusive, of each year, lands within Montana and North Dakota shall be entitled to the beneficial use of the flow of waters of the Yellowstone River below Intake, Montana, on a proportionate basis of acreage irrigated. Waters of tributary streams, having their origin in either Montana or North Dakota, situated entirely in said respective States and flowing into the Yellowstone River below Intake, Montana, are allotted to the respective States in which situated.

E. There are hereby excluded from the provisions of this Compact:

1. Existing and future domestic and stock water uses of water: Provided, that the capacity of any reservoir for stock water so excluded shall not exceed twenty (20) acre-feet;

2. Devices and facilities for the control and regulation of surface waters.

F. From time to time the Commission shall reexamine the allocations herein made and upon unanimous agreement may recommend modifications therein as are fair, just, and equitable, giving consideration among other factors to:

1. Priorities of water rights;

2. Acreage irrigated;

3. Acreage irrigable under existing works; and

4. Potentially irrigable lands.

ARTICLE VI

Nothing contained in this Compact shall be as construed or interpreted as to affect adversely any rights to the use of the waters of Yellowstone River and its tributaries owned by or for Indians, Indian tribes, and their reservations.

ARTICLE VII

A. A lower signatory State shall have the right, by compliance with the laws of an upper signatory State, except as to legislative consent, to file application for and receive permits to appropriate and use any waters in the Yellowstone River System not specifically apportioned to or appropriated by such upper State as provided in Article V; and to construct or participate in the construction and use of any dam, storage reservoir, or diversion works in such upper State for the purpose of conserving and regulating water that may be apportioned to or appropriated by the lower State: provided, that such right is subject to the rights of the upper State to control, regulate, and use the water apportioned to and appropriated by it: and provided further, that should an upper State elect, it may share in the use of any such facilities constructed by a lower State to the extent of its reasonable needs upon assuming or guaranteeing payment of its proportionate share of the cost of the construction, operation, and maintenance. This provision shall apply with equal force and effect to an upper State in the circumstance of the necessity of the acquisition of rights by an upper State in a lower State.

B. Each claim hereafter initiated for an appropriation of water in one signatory State for use in another signatory State shall be filed in the office of the State Engineer of the signatory State in which the water is to be diverted, and a duplicate copy of the application or notice shall be filed in the office of the State Engineer of the signatory State in which the water is to be used.

C. Appropriations may hereafter be adjudicated in the State in which the water is diverted, and where a portion or all of the lands irrigated are in another signatory State, such adjudications shall be confirmed in that State by the proper authority. Each adjudication is to conform to the laws of the State where the water is diverted and shall be recorded in the County and State where the water is used.

D. The use of water allocated under Article V of this Compact for projects constructed after the date of this Compact by the United States of America or any of its agencies or instrumentalities, shall be charged as a use by the State in which the use is made: Provided, that such use incident to the diversion, impounding, or conveyance of water in one State for use in another shall be charged to such latter State.

ARTICLE VIII

A lower signatory State shall have the right to acquire in an upper State by purchase, or through exercise of the power of eminent domain, such lands, easements, and rights-of-way for the construction, operation, and maintenance of pumping plants, storage reservoirs, canals, conduits, and appurtenant works as may be required for the enjoyment of the privileges granted herein to such lower State. This provision shall apply with equal force and effect to an upper State in the circumstance of the necessity of the acquisition of rights by an upper State in a lower State.

ARTICLE IX

Should any facilities be constructed by a lower signatory State in an upper signatory State under the provisions of Article VII, the construction, operation, repairs, and replacements of such facilities shall be subject to the laws of the upper State. This provision shall apply with equal force and effect to an upper State in the circumstance of the necessity of the acquisition of rights by an upper State in a lower State.

ARTICLE X

No water shall be diverted from the Yellowstone River Basin without the unanimous consent of all the signatory States. In the event water from another river basin shall be imported into the Yellowstone River Basin or transferred from one tributary basin to another by the United States of America, Montana, North Dakota, or Wyoming, or any of them jointly, the state having the right to the use of such water shall be given proper credit therefore in determining its share of the water apportioned in accordance with Article V herein.

ARTICLE XI

The provisions of this Compact shall remain in full force and effect until amended in the same manner as it is required to be ratified to become operative as provided in Article XV.

ARTICLE XII

This Compact may be terminated at any time by unanimous consent of the signatory States, and upon such termination all rights then established hereunder shall continue unimpaired.

ARTICLE XIII

Nothing in this Compact shall be construed to limit or prevent any State from instituting or maintaining any action or proceeding, legal or equitable, in any Federal Court or the United States Supreme Court, for the protection of any right under this Compact or the enforcement of any of its provisions.

ARTICLE XIV

The physical and other conditions characteristic of the Yellowstone River and peculiar to the territory drained and served thereby and to the development thereof, have actuated the signatory States in the consummation of this Compact, and none of them, nor the United States of America by its consent and approval, concedes thereby the establishment of any general principle or precedent with respect to other interstate streams.

ARTICLE XV

This Compact shall become operative when approved by the Legislature of each of the signatory States and consented to and approved by the Congress of the United States.

ARTICLE XVI

Nothing in this Compact shall be deemed:

(a) To impair or affect the sovereignty or jurisdiction of the United States of America in or over the area of waters affected by such compact, any rights or powers of the United States of America, its agencies, or instrumentalities, in and to the use of the waters of the Yellowstone River Basin nor its capacity to acquire rights in and to the use of said waters;

(b) To subject any property of the United States of America, its agencies, or instrumentalities to taxation by any State or subdivision thereof, nor to create an obligation on the part of the United States of America, its agencies, or instrumentalities, by reason of the acquisition, construction, or operation of any property or works of whatsoever kind, to make any payments to any State or political subdivision thereof, State agency, municipality, or entity whatsoever in reimbursement for the loss of taxes;

(c) To subject any property of the United States of America, its agencies, or instrumentalities, to the laws of any State to an extent other than the extent to which these laws would apply without regard to the Compact.

ARTICLE XVII

Should a Court of competent jurisdiction hold any part of this Compact to be contrary to the Constitution of any signatory State or of the United States of America, all other severable provisions of this Compact shall continue in full force and effect.

ARTICLE XVIII

No sentence, phrase, or clause in this Compact or in any provision thereof, shall be construed or interpreted to divest any signatory State or any of the agencies or officers of such States of the jurisdiction of the water of each State as apportioned in this Compact.

IN WITNESS WHEREOF the Commissioners have signed this Compact in quadruplicate original, one (1) of which shall be filed in the archives of the Department of State of the United States of America and shall be deemed the authoritative original, and of which a duly certified copy shall be forwarded to the Governor of each signatory State.

Done at the city of Billings in the state of Montana, this 8th day of December, in the year of our Lord, One Thousand Nine Hundred and Fifty.

Commissioners for the State of Montana:

Fred E. Buck
A. W. Bradshaw
H. W. Bunston
John Herzog
John M. Jarussi
Ashton Jones
Chris Josephson
A. Wallace Kingsbury

P. F. Leonard
Walter M. McLaughlin
Dave M. Manning
Joseph Muggli
Chester E. Onstad
Ed F. Parriott
R. R. Renne
Keith W. Trout

Commissioners for the State of North Dakota:

I. A. Acker
J. J. Walsh
Einar H. Dahl

Commissioners for the State of Wyoming

L. C. Bishop
Earl T. Bower
J. Harold Cash
Ben F. Cochrane
Ernest J. Goppert
Richard L. Greene
E. C. Gwillim
E. J. Johnson
Lee E. Keith
N. V. Kurtz
Harry L. Littlefield
R. E. McNally
Will G. Metz
Mark N. Partridge
Alonzo R. Shreve
Charles M. Smith
Leonard F. Thornton
M. B. Walker

I have participated in the negotiation of this Compact and intend to report favorably thereon to the Congress of the United States.

R. J. Newell

Representative of the United States of America.

NOTES

Congressional Consent to Negotiations. --- By the Act of June 2, 1949 (63 Stat. 152), the Congress gave its consent to the negotiation by the States of Montana, North Dakota and Wyoming of a Yellowstone River Compact or agreement not later than June 1, 1952. The consent was upon condition "one suitable person, who shall be appointed by the President of the United States shall participate in said negotiations as the Representative of the United States and shall make a report to Congress of proceedings and of any compact or agreement entered into." The Act further provided that the compact or agreement should not be effective until "approved" by the legislatures of the States and by the Congress and that "nothing in this Act shall apply to any waters within or tributary to the Yellowstone National Park or shall establish any right or interest in or to any lands within the boundaries thereof."

In a letter to Robert Newell, the Federal Representative on the Yellowstone River Compact negotiating team, the President expressed his views on certain possible compact provisions by reference to the recently approved Snake River Compact. The text of the letter and an attached memorandum from the Director of the Bureau of the Budget follow:

"May 3, 1950

"MY DEAR MR. NEWELL: The purpose of this letter is to call your attention to a problem of growing concern and, in the solution of which, the Federal Representatives assigned to interstate water compact commissions are in a position to perform a valuable public service. I refer to the somewhat recent tendency to incorporate in interstate water compacts questionable or conflicting provisions imposing restrictions on use of waters by the United States, such as appear in the Snake River Compact enactment, which I approved on March 21, 1950 (Public Law 464, 8lst Congress, 2nd Session).

"In this particular case, the possibility of misinterpretation of certain apparently conflicting provisions was not considered to be serious enough to warrant withholding approval of the enrolled enactment of the Congress (S. 3159). Such provisions however, if followed as precedent for general application, may jeopardize the prospect of consent and approval of compacts by the Federal Government because of the far reaching effects such provisions might have upon the interests of the United States. This matter is further discussed in a memorandum to me from the Director of the Bureau of the Budget, a copy of which is enclosed for your information and guidance.

"I fully realize how difficult it is to resolve the numerous Complex jurisdictional and other problems encountered in reaching agreement upon the allocation of waters of an interstate stream. At the same time, I am impressed with the importance of insuring that compact provisions reflect as clearly as possible a recognition of the respective responsibilities and prerogatives of the United States and the affected States. I can assure you that any efforts made by you and the other compact commissioners with whom you have occasion to collaborate in eliminating or correcting this area of possible conflict, will be appreciated.

"Sincerely yours,

"Harry S. Truman"

"April 21, 1950

"Memorandum for the President:

"Analysis of the enrolled enactment granting the consent and approval of the Congress to the Snake River Compact, prior to your approval on March 21,1950, (Public Law 464, 8lst Congress, 2nd Session), revealed the possibility of misinterpretation of certain apparently conflicting provisions, which did not appear to be serious enough in this particular case to provide a sound basis for recommending disapproval of the bill, but which, if followed as precedent for general application, might have far reaching effects upon the interests of the United States. The conflicts arise primarily between specific provisions imposing restrictions upon uses of water by the United States for power and other purposes, and the general savings clause in Article XIV. This article provides that nothing in the compact shall be deemed to impair or affect any rights or powers of the United States in and to the use of the waters of the Snake River nor its capacity to acquire rights in and to the use of said waters. By reason of such conflicts, doubts may rise as to the extent of the control which the States concerned may exercise over the rights, interests and structures owned or built by the United States on the river. The resulting possibility of confusion thus tends to defeat one of the basic purposes of the compact, of settling the respective rights and interests of the Federal and State Governments in, over and to the river.

"The Committee on Public Lands of the House of Representatives, in its report on the bill (S. 3159) recorded its interpretation of the term "beneficial uses" appearing in Article XIV-B, as not regarded by the Committee as including the use and control of water by the United States by reason of its power with respect to navigable waters under the commerce clause of the Constitution (H. R. Report No. 1743, 8lst Congress, 2nd Session). It is also significant that the Congress saw fit to include in the enactment a provision (Section 2) expressly preserving to the United States the right to alter, amend, and repeal the Act at any time.

"Somewhat similar provisions appear in the proposed Cheyenne River Compact now pending before Congress (H. R. 3336 and S. 1211) and in the Republican River Compact approved May 26, 1943, and the Belle Fourche River Basin Compact approved February 26, 1944. In approving each of these latter enactments, President Roosevelt issued a statement emphasizing that the procedure prescribed by the bill for exercise of the powers of the Federal Government, would not be entirely satisfactory in all circumstances and that these compacts should not serve as precedents, particularly for streams where there appears to be a possible need for Federal comprehensive multiple purpose development or where opportunities for important electric power projects are present. Likewise the Snake River Compact should not serve as a precedent.

"In its report in S. 3159 the Public Lands Committee of the Senate expressed the view that the compact method is the logical and proper manner to settle interstate water controversies. With this view I am in accord but I am also mindful that compact provisions, which are subject to misinterpretation or leave in doubt the respective rights and interests of the United States and the affected States, serve to impair these rights. It is obvious therefore, that the compact method places upon the compact commissioners the important responsibility of drawing compacts in specific and unequivocal language, devoid of all possible ambiguity, and which do not attempt to define, limit or otherwise determine the extent of the powers to be exercised by the United States which is a matter for determination by the Congress through Federal legislation as required.

"The importance of insuring that future compacts more adequately reflect a clear recognition of the respective responsibilities and prerogatives of the United States and the affected States, I believe is readily apparent. In formulating provisions of interstate water compacts, which impose restrictions upon use by the United States of waters in the streams concerned, the responsibility for protecting the rights and interests of the United States rests in the first instance upon those appointed to represent the Federal Government in negotiations with the State compact commissions. The Federal Representatives also are in a position to assist the compact commission in avoiding further use of questionable or conflicting provisions similar to the aforementioned, in order to minimize the possibility of disapproval of the compact by the State legislatures or the Federal Government, or the later possibility of prolonged and costly litigation.

"F.J. Lawton"

"Director"

Congressional Consent to and Legislative History of the Compact. --- Act of October 30, 1951 (65 Stat. 663) from which the text of the Compact set out above is taken. Section 2 of this Act read as follows:

"The right to alter, amend or repeal Section 1 of this Act is expressly reserved. This reservation shall not be construed to prevent the vesting of rights to the use of water pursuant to applicable law and no alteration, amendment or repeal of Section 1 of this Act shall be held to affect rights so vested."

For legislative history, see S. 1311 and H.R. 3544, 82nd Congress; Senate Report 883 (Committee on Interior and Insular Affairs) and House Report 1118 (Committee on Interior and Insular Affairs), 82nd Congress; 97 Cong. Rec. 12954-12956, 13478-13480 (1951); P.L. 231, 82nd Congress

UPPER NIOBRARA RIVER COMPACT, 1962

Signatory States:	Nebraska and Wyoming
Rivers Controlled:	The Niobrara River and its tributaries in Nebraska and Wyoming west of Range 55 West of the 6th Principal Meridian.
Ratifications:	Wyo. Stat. §4l-512.5 (Supp. 1969) [Act of Feb. 16, 1963, Wyo. Sess. Laws, ch. 105]
	Neb. Rev. Stat. vol. 2A, app. §1-112 (1995) [Act of Oct. 26, 1962, 1963 Neb. Laws, ch. 332]
Summary:	The Compact provides for only limited restrictions on Wyoming's use of the Niobrara River. Basically, these restrictions relate to: 1) priority dates and storage rights in Wyoming reservoirs and 2) priority dates and direct flow reights in the Niobrara, its tributaries and ditches. The Compact also lays the foundation for future apportionment of the ground water in the Niobrara River Basin.

UPPER NIOBRARA RIVER COMPACT, 1962

The State of Wyoming, and the State of Nebraska, parties signatory to this Compact (hereinafter referred to as Wyoming and Nebraska, respectively, or individually as a "State" or collectively as "States"), having resolved to conclude a compact with respect to the use of waters of the Niobrara River Basin, and being duly authorized by Act of Congress of the United States of America, approved August 5, 1953 (Public Law 191, 83rd Congress, 1st Session, Chapter 324, 67 Stat. 365) and the Act of May 29, 1958 (Public Law 85-427, 85th Congress, S. 2557, 72 Stat. 147) and the Act of August 30, 1961 (Public Law 87-181, 87th Congress, S. 2245, 75 Stat. 412) and pursuant to the Acts of their respective Legislatures have, through their respective Governors, appointed as their commissioners: for Wyoming, Earl Lloyd, Andrew McMaster, Richard Pfister, John Christian, Eugene P. Willson, H. T. Person, Norman B. Gray, E. J. Van Camp; For Nebraska, Dan S. Jones, Jr., who after negotiations participated in by W. E. Blomgren appointed by the President of the United States of America, have agreed upon the following articles:

ARTICLE I

A. The major purposes of this Compact are to provide for an equitable division or apportionment of the available surface waters supply of the Upper Niobrara River Basin between the states; to provide for obtaining information or groundwater and underground water flow necessary for apportioning the underground flow by supplement to this Compact; to remove all causes, present and future which might lead to controversies; and to promote interstate comity.

B. The physical and other conditions peculiar to the upper Niobrara River Basin constitute the basis for this Compact, and neither of the States hereby concedes that this Compact establishes any general principle or precedent with respect to any other interstate stream.

C. Either State and all others using, claiming or in any other manner asserting any right to the use of the waters of the Niobrara River Basin under the authority of that State, shall be subject to the terms of this Compact.

ARTICLE II

A. The term "Upper Niobrara River" shall mean and include the Niobrara River and its tributaries in Nebraska and Wyoming west of Range 55 West of the 6th P. M.

B. The term "Upper Niobrara River Basin" or the term "Basin" shall mean that area in Wyoming and Nebraska, which is naturally drained by the Niobrara River west of Range 55 West of the 6th P. M.

C. Where the name of a State or the term "State" or "States" is used, they shall be construed to include any person or entity of any nature whatsoever using, claiming, or in any manner asserting any right to the use of the waters of the Niobrara River under the authority of that State.

ARTICLE III

It shall be the duty of the two (2) States to administer this Compact through the official in each State who is now or may hereafter be charged with the duty of administering the public water supplies, and to collect and correlate through such officials the data necessary for the proper administration of the provisions of this Compact. Such officials may, by unanimous action, adopt rules and regulations consistent with the provisions of this Compact.

The States agree that the United States Geological Survey, or whatever federal agency may succeed to the functions and duties of that agency, insofar as this Compact is concerned, may collaborate with the officials of the States charged with the administration of this Compact in the execution of the duty of such officials in the collection, correlation, and publication of information necessary for the proper administration of this Compact.

ARTICLE IV

Each State shall itself or in conjunction with other responsible agencies cause to be established, maintained, and operated such suitable water gaging stations as are found necessary to administer this Compact.

ARTICLE V

A. Wyoming and Nebraska agree that the division of surface waters of the Upper Niobrara River shall be in accordance with the following provisions:

1. There shall be no restrictions on the use of the surface waters of the Upper Niobrara River by Wyoming except as would be imposed under Wyoming law and the following limitations:

(a) No reservoir constructed after August 1, 1957, and used solely for domestic and stock water purposes shall exceed twenty (20) acre-feet in capacity.

(b) Storage reservoirs with priority dates after August 1, 1957, and storing water from the main stem of the Niobrara River east of Range 62 West of the 6th P. M. and from the main stem of Van Tassel Creek south of Section 27, Township 32 North, Range 60 West of the 6th P. M. shall not store in any water year (October 1 of one (1) year to September 30 of the next year) more than a total of 500 acre-feet of water.

(c) Storage in reservoirs with priority dates prior to August 1, 1957, and storing water from the main stem of the Niobrara River East of Range 62 West and from the main stem of Van Tassel Creek south of Section 27, Township 32 North, shall be made only during the period October 1 of one (1) year to June 1 of the next year and at such times during the period June 1 to September 30 that the water is not required to meet the legal requirements by direct flow appropriations in Wyoming and Nebraska west of Range 55 West. Where water is pumped from such storage reservoirs, the quantity of storage water pumped or otherwise diverted for irrigation purposes or other beneficial purposes from any such reservoir in any water year shall be limited to the capacity of such reservoir as shown by the records of the Wyoming State Engineer's Office, unless additional storage water becomes available during the period June 1 to September 30 after meeting the legal diversion requirements by direct flow appropriations in Wyoming and Nebraska west of Range 55 West.

(d) Storage in reservoirs with priority dates after August 1, 1957 and storing water from the main stem of the Niobrara River east of Range 62 West and the main stem of Van Tassel Creek south of Section 27, Township 32 North, shall be made only during the period October 1 of one (1) year to May 1 of the next year and at such times during the period May 1 and September 30 that the water is not required for direct diversion by ditches in Wyoming and in Nebraska west of Range 55 West.

(e) Direct flow rights with priority dates after August 1, 1957, on the main stem of the Niobrara River east of Range 62 West and Van Tassel Creek south of Section 27, Township 32 North, shall be regulated on a priority basis with Nebraska rights west of Range 55 West, provided that any direct flow rights for maximum of 143 acres which may be granted by the Wyoming State Engineer with a priority date not later than July 1, 1961 for lands which had territorial rights under the Van Tassel No. 4 Ditch with a priority date of April 8, 1882, and the Van Tassel No. 5 Ditch with a priority date of April 18, 1882, shall be exempt from the provisions of this subsection (e).

(f) All direct flow diversions from the main stem of the Niobrara River east of Range 62 West and from Van Tassel Creek south of Section 27, Township 32 North shall at all times be limited to their diversion rates as specified by Wyoming law, and provided that Wyoming laws relating to diversion of "surplus water" (W.S. 41-4-317 through 41-4-324) shall apply only when the water flowing in the main channel of the Niobrara River west of Range 55 West is in excess of the legal diversion requirements of Nebraska ditches having priority dates before August 1, 1957.

ARTICLE VI

A. Nebraska and Wyoming recognize that the future use of ground water for irrigation in the Niobrara River basin may be a factor in the depletion of the surface flows of the Niobrara River, and since the data now available are inadequate to make a determination in regard to this matter, any apportionment of the ground water of the Niobrara River Basin should be delayed until such time as adequate data on ground water of the basin are available.

B. To obtain data on ground water, Nebraska and Wyoming, with the cooperation and advice of the United States Geological Survey, Groundwater Branch, shall undertake ground water investigations in the Niobrara River basin in the area of the Wyoming-Nebraska State line. The investigations shall be such as are agreed to by the State Engineer of Wyoming and the Director of Water Resources of Nebraska, and may include such observation wells as the said two officials agree are essential for the investigations. Costs of the investigations may be financed under the cooperative ground water programs between the United States Geological Survey and the States, and the States' share of the costs shall be borne equally by the two States.

C. The ground water investigations shall begin within one year after the effective date of this Compact. Upon collection of not more than twelve months of ground water data Nebraska and Wyoming with the cooperation of the United States Geological Survey shall make, or cause to be made an analysis of such data to determine the desirability or necessity of apportioning the ground water by supplement to this Compact. If, upon completion of the initial analysis, it is determined that apportionment of the ground water is not then desirable or necessary, re-analysis shall be made at not to exceed two-year intervals, using all data collected until such apportionment is made.

D. When the results of the ground water investigations indicate that apportionment of ground water of the Niobrara River Basin is desirable, the two States shall proceed to negotiate a supplement to this Compact apportioning the ground water of the Basin.

E. Any proposed supplement to this Compact apportioning the ground water shall not become effective until ratified by the legislatures of the two States and approved by the Congress of the United States.

ARTICLE VII

The provisions of this Compact shall remain in full force and effect until amended by action of the Legislatures of the signatory States and until such amendment is consented to and approved by the Congress of the United States in the same manner as this Compact is required to be ratified and consented to in order to become effective.

ARTICLE VIII

Nothing in this Compact shall be construed to limit or prevent either State from instituting or maintaining any action or proceeding, legal or equitable, in any court of competent jurisdiction for the protection of any right under this Compact or the enforcement of any of its provisions.

ARTICLE IX

Nothing in this Compact shall be deemed:

A. To impair or affect any rights or powers of the United States, its agencies, or instrumentalities, in and to the use of the waters of the Upper Niobrara River Basin nor its capacity to acquire rights in and to the use of said waters; provided that any beneficial uses of the waters allocated by this Compact hereafter made within a State by the United States, or those acting by or under its authority, shall be taken into account in determining the extent of use within that State.

B. To subject any property of the United States, its agencies, or instrumentalities to taxation by either State or subdivision thereof, nor to create an obligation on the part of the United States, its agencies, or instrumentalities, by reason of the acquisition, construction or operation of any property or works of whatsoever kind, to make any payment to any State or political subdivision thereof, State agency, municipality, or equity whatsoever in reimbursement for the loss of taxes.

C. To subject any property of the United States, its agencies, or instrumentalities, to the laws of any State to an extent other than the extent to which these laws apply without regard to the Compact.

D. To affect the obligations of the United States of America to Indians or Indian tribes, or any right owned or held by or for Indians or Indian tribes, which is subject to the jurisdiction of the United States.

ARTICLE X

Should a court of competent jurisdiction hold any part of this Compact contrary to the Constitution of any State or of the United States, all other severable provisions shall continue in full force and effect.

ARTICLE XI

This Compact shall become effective when ratified by the Legislatures of each of the signatory States and by the Congress of the United States.

IN WITNESS WHEREOF, the commissioners have signed this Compact in triplicate original, one of which shall be filed in the archives of the United States of America and shall be deemed the authoritative original, and one copy of which shall be forwarded to the Governor of each of the signatory States.

Done at the city of Cheyenne, in the state of Wyoming, this 26th day of October, in the year of our Lord, One Thousand Nine Hundred Sixty-Two, 1962.

Commissioners for the State of Nebraska

Dan S. Jones, Jr.

Commissioners for the State of Wyoming

Earl Lloyd
Andrew McMaster
Richard Pfister
John Christian
Eugene P. Wilson
H. T. Person
Norman B. Gray
E. J. Van Camp

I have participated in the negotiation of this Compact and intend to report favorably thereon to the Congress of the United States.

W. E. Blomgren

Representative of the United States of America.

NOTES

Congressional Consent to Negotiation. --- By the Act of August 5, 1953 (67 Stat. 365) the Congress gave its consent to negotiations between the States of Wyoming and Nebraska. The time for negotiation was extended by the Act of May 29, 1958 (72 Stat. 147) and again by the Act of August 30, 1961 (75 Stat. 412)

Congressional Consent to Compact. --- Act of August 4, 1969 (83 Stat. 86) from which the text of the Compact set out above is taken. Sections 2 and 3 of this Act read as follows:

Section 2: The right to alter, amend or repeal this Act is reserved.

Section 3. Nothing in this Act shall be deemed to impair or affect any rights or powers of the United States, its agencies, instrumentalities, permittees or licensees in, over, and to the use of the waters of the Upper Niobrara River Basin; nor to impair or affect their capacity to acquire rights in and to the use of said waters.

Legislative History of the Compact. --- For legislative history, see House Report No. 91-359 (Committee on Interior and Insular Affairs); Senate Report No 91-265 (Committee on Interior and Insular Affairs); Cong. Rec. vol. 115 (1969); and Public Law 91-52.

Appendix E-1

Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the NERB excluding Wind River structural basin, Wyoming

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Quaternary alluvial aquifers	Dissolved oxygen	25	0.20	0.30	0.80	5.6	9.1
	pH (standard units)	65	6.9	7.1	7.4	7.6	8.7
	Specific conductance (µS/cm)	65	174	1,040	1,640	2,730	6,000
	Hardness (as $CaCO_3$)	65	77.0	331	570	1,160	2,600
	Calcium	65	19.0	70.0	116	273	540
	Magnesium	65	5.2	33.3	63.0	120	370
	Potassium	61	1.0	3.0	6.7	13.0	30.0
	Sodium	65	5.7	35.0	149	306	970
	Sodium adsorption ratio (unitless)	65	0.19	0.75	2.0	5.4	30.0
	Alkalinity (as $CaCO_3$)	65	72.0	308	373	502	720
	Chloride	64	0.08	5.6	9.7	67.5	290
	Fluoride	64	0.10	0.23	0.40	0.60	1.2
	Silica	64	2.5	11.0	13.3	17.0	35.0
	Sulfate	65	7.1	150	450	1,220	2,700
	Total dissolved solids	65	106	649	1,140	2,110	4,880
	Ammonia (as N)	51	--	0.001	0.005	0.05	2.1
	Ammonia plus organic nitrogen (as N)	8	0.08	0.11	0.14	0.16	0.17
	Ammonia plus organic nitrogen, unfiltered (as N)	5	1.1	1.3	1.9	2.3	3.8
	Ammonia, unfiltered (as N)	17	--	0.003	0.01	0.09	1.9
	Dissolved organic carbon	25	0.64	1.7	2.4	3.0	4.6
	Nitrate (as N)	71	0.02	0.06	0.20	1.4	30.0
	Nitrate plus nitrite (as N)	52	0.03	0.08	0.27	2.8	21.0
	Nitrate, unfiltered (as N)	12	0.11	0.11	0.75	2.7	5.5
	Nitrate+nitrite, unfiltered (as N)	5	0.05	0.08	0.11	0.12	0.45
	Nitrite (as N)	51	--	0.001	0.002	0.005	0.16
	Nitrite, unfiltered (as N)	12	--	0.0005	0.002	0.02	0.11
	Organic nitrogen	8	--	--	--	--	<0.17
	Organic nitrogen, unfiltered	20	0.01	0.02	0.07	0.33	2.1
	Orthophosphate (as P)	51	--	0.005	0.01	0.02	0.31
	Phosphorus	8	0.004	0.006	0.008	0.01	0.01
	Phosphorus, unfiltered	9	0.13	0.13	0.26	0.41	2.5
	Total nitrogen	8	--	0.19	0.32	0.56	1.5
	Total nitrogen, unfiltered	5	1.2	1.7	2.0	2.3	3.9
	Total nitrogen, unfiltered, analytically determined	17	0.15	0.20	0.72	2.7	5.1
	Aluminum	30	--	0.40	1.4	4.6	30.0
	Antimony	30	0.04	0.05	0.11	0.25	2.0
	Arsenic	32	0.20	0.27	0.48	0.85	4.1

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Quaternary alluvial aquifers —Continued	Barium	27	8.4	30.0	51.9	89.6	170
	Beryllium	30	<0.06	--	--	--	10.0
	Boron	56	40.0	100	165	290	950
	Cadmium	32	--	--	--	--	<5.0
	Chromium	30	--	0.25	0.57	1.3	20.0
	Cobalt	25	0.12	0.17	0.24	0.33	0.53
	Copper	29	--	0.94	1.8	3.4	27.0
	Iron	30	--	0.15	2.2	31.0	4,300
	Iron, unfiltered	48	10.0	54.8	255	3,050	110,000
	Lead	32	--	0.01	0.06	0.27	4.0
	Lithium	13	8.0	18.1	23.5	120	170
	Manganese	30	0.09	1.3	37.0	190	13,000
	Manganese, unfiltered	22	--	2.4	53.0	780	13,000
	Mercury	5	--	--	--	--	<0.5
	Molybdenum	30	0.32	1.3	8.9	15.0	22.0
	Nickel	30	0.20	0.50	1.0	2.0	14.0
	Selenium	32	--	0.33	0.94	2.7	22.0
	Strontium	25	140	460	577	1,100	8,100
	Vanadium	29	0.40	0.56	0.96	1.7	3.6
	Zinc	30	--	0.16	0.83	4.3	230
	Radon-222, in pCi/L	9	500	680	850	1,190	1,440
	Tritium, unfiltered, in pCi/L	4	37.1	42.9	50.7	62.7	72.6
	Uranium	20	1.4	4.0	8.8	13.5	83.0
Quaternary terrace-deposit aquifers	Dissolved oxygen	2	1.4	--	--	--	6.5
	pH (standard units)	2	7.2	--	--	--	7.4
	Specific conductance (µS/cm)	2	923	--	--	--	1,320
	Hardness (as $CaCO_3$)	2	281	--	--	--	429
	Calcium	2	68.0	--	--	--	77.0
	Magnesium	2	27.0	--	--	--	57.0
	Potassium	2	2.4	--	--	--	6.0
	Sodium	2	36.0	--	--	--	210
	Sodium adsorption ratio (unitless)	2	0.75	--	--	--	5.4
	Alkalinity (as $CaCO_3$)	2	388	--	--	--	424
	Chloride	2	14.0	--	--	--	36.0
	Fluoride	2	0.40	--	--	--	0.50
	Silica	2	15.0	--	--	--	19.0
	Sulfate	2	75.0	--	--	--	290
	Total dissolved solids	2	536	--	--	--	861

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Quaternary terrace-deposit aquifers—Continued	Ammonia (as N)	2	<0.025	--	--	--	1.3
	Ammonia, unfiltered (as N)	1	<0.03	--	--	--	--
	Dissolved organic carbon	2	1.9	--	--	--	1.9
	Nitrate (as N)	2	<0.05	--	--	--	1.8
	Nitrate plus nitrite (as N)	1	<0.05	--	--	--	--
	Nitrate, unfiltered (as N)	1	1.2	--	--	--	--
	Nitrite (as N)	2	--	--	--	--	<0.01
	Nitrite, unfiltered (as N)	1	0.005	--	--	--	--
	Organic nitrogen, unfiltered	1	<1.7	--	--	--	--
	Orthophosphate (as P)	2	<0.01	--	--	--	0.08
	Total nitrogen, unfiltered, analytically determined	2	1.2	--	--	--	1.7
	Aluminum	2	--	--	--	--	<100
	Antimony	2	--	--	--	--	<1.0
	Arsenic	2	--	--	--	--	<4.0
	Barium	2	15.0	--	--	--	150
	Beryllium	2	--	--	--	--	<1.0
	Boron	2	100	--	--	--	110
	Cadmium	2	--	--	--	--	<0.2
	Chromium	2	--	--	--	--	<5.0
	Cobalt	2	--	--	--	--	<2.0
	Copper	2	--	--	--	--	<5.0
	Iron	2	--	--	--	--	<100
	Iron, unfiltered	2	--	--	--	--	<100
	Lead	2	--	--	--	--	<1.0
	Manganese	2	<2.0	--	--	--	11.0
	Manganese, unfiltered	2	<2.0	--	--	--	14.0
	Molybdenum	2	10.0	--	--	--	12.0
	Nickel	2	--	--	--	--	<4.0
	Selenium	2	1.4	--	--	--	2.0
	Strontium	2	690	--	--	--	840
	Vanadium	2	--	--	--	--	<10.0
	Zinc	2	--	--	--	--	<50.0
	Radon-222, in pCi/L	1	1,270	--	--	--	--
	Uranium	1	10.0	--	--	--	--
Quaternary dune sand (eolian) deposits	pH (standard units)	2	8.3	--	--	--	8.4
	Specific conductance (µS/cm)	2	2,030	--	--	--	2,750
	Hardness (as $CaCO_3$)	2	243	--	--	--	634
	Calcium	2	64.0	--	--	--	165

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Quaternary dune sand (eolian) deposits —Continued	Magnesium	2	20.2	--	--	--	54.0
	Potassium	2	6.5	--	--	--	8.5
	Sodium	2	356	--	--	--	410
	Sodium adsorption ratio (unitless)	2	7.1	--	--	--	9.9
	Alkalinity (as $CaCO_3$)	2	225	--	--	--	295
	Chloride	2	99.0	--	--	--	151
	Fluoride	1	0.80	--	--	--	--
	Silica	1	12.0	--	--	--	--
	Sulfate	2	472	--	--	--	1,100
	Total dissolved solids	2	1,340	--	--	--	2,110
	Nitrate plus nitrite (as N)	1	9.4	--	--	--	--
	Boron	1	290	--	--	--	--
	Iron, unfiltered	2	<30.0	--	--	--	30.0
Quaternary landslide deposits	pH (standard units)	1	8.1	--	--	--	--
	Specific conductance (µS/cm)	1	166	--	--	--	--
	Calcium	1	29.0	--	--	--	--
	Magnesium	1	9.0	--	--	--	--
	Potassium	1	2.0	--	--	--	--
	Sodium	1	3.0	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.12	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	94.3	--	--	--	--
	Chloride	1	1.0	--	--	--	--
	Fluoride	1	0.10	--	--	--	--
	Silica	1	21.0	--	--	--	--
	Sulfate	1	17.0	--	--	--	--
	Total dissolved solids	1	124	--	--	--	--
Quaternary glacial deposits	pH (standard units)	1	6.7	--	--	--	--
	Specific conductance (µS/cm)	1	99.0	--	--	--	--
	Hardness (as $CaCO_3$)	1	38.0	--	--	--	--
	Calcium	1	10.0	--	--	--	--
	Magnesium	1	3.2	--	--	--	--
	Potassium	1	1.0	--	--	--	--
	Sodium	1	4.7	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.30	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	48.0	--	--	--	--
	Chloride	1	0.10	--	--	--	--

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Quaternary glacial deposits —Continued	Fluoride	1	0.10	--	--	--	--
	Silica	1	21.0	--	--	--	--
	Sulfate	1	3.3	--	--	--	--
	Total dissolved solids	1	82.0	--	--	--	--
	Nitrate (as N)	1	0.02	--	--	--	--
	Boron	1	10.0	--	--	--	--
	Iron, unfiltered	1	220	--	--	--	--
Tertiary intrusive igneous rocks	pH (standard units)	1	6.6	--	--	--	--
	Specific conductance (µS/cm)	1	105	--	--	--	--
	Hardness (as $CaCO_3$)	1	40.0	--	--	--	--
	Calcium	1	13.0	--	--	--	--
	Magnesium	1	1.8	--	--	--	--
	Potassium	1	1.3	--	--	--	--
	Sodium	1	3.5	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.20	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	38.0	--	--	--	--
	Chloride	1	0.70	--	--	--	--
	Fluoride	1	0.30	--	--	--	--
	Silica	1	18.0	--	--	--	--
	Sulfate	1	8.2	--	--	--	--
	Total dissolved solids	1	80.0	--	--	--	--
	Nitrate (as N)	1	0.54	--	--	--	--
	Boron	1	10.0	--	--	--	--
	Iron, unfiltered	1	30.0	--	--	--	--
	Tritium, unfiltered, in pCi/L	1	41.9	--	--	--	--
Arikaree aquifer	Dissolved oxygen	27	0.80	5.3	7.2	8.3	11.9
	pH (standard units)	52	7.0	7.5	7.6	7.9	8.6
	Specific conductance (µS/cm)	56	199	366	402	539	1,530
	Hardness (as $CaCO_3$)	42	106	160	180	240	544
	Calcium	57	31.0	49.0	56.0	68.0	192
	Magnesium	57	5.4	10.0	13.0	18.0	50.0
	Potassium	57	2.6	6.2	7.5	9.0	29.0
	Sodium	57	5.4	9.0	12.0	19.0	83.0
	Sodium adsorption ratio (unitless)	57	0.19	0.30	0.36	0.60	1.6
	Alkalinity (as $CaCO_3$)	57	110	170	187	223	449
	Chloride	57	1.0	3.5	7.0	14.0	141
	Fluoride	45	0.10	0.20	0.30	0.40	0.60

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Arikaree aquifer —Continued	Silica	53	23.0	53.9	56.0	58.0	74.0
	Sulfate	57	1.1	8.1	15.0	27.0	293
	Total dissolved solids	56	198	263	285	373	1,150
	Ammonia (as N)	25	--	--	--	--	<0.25
	Dissolved organic carbon	22	0.43	0.82	0.99	2.3	16.3
	Nitrate (as N)	31	0.16	2.0	2.8	5.6	23.0
	Nitrate plus nitrite (as N)	17	0.16	1.9	2.7	3.4	25.0
	Nitrite (as N)	27	--	0.001	0.002	0.003	0.01
	Organic nitrogen	1	<0.08	--	--	--	--
	Organic nitrogen, unfiltered	21	--	--	--	--	<19
	Orthophosphate (as P)	23	0.06	0.10	0.13	0.15	124
	Phosphorus, unfiltered	5	<0.03	--	--	--	0.07
	Total nitrogen, unfiltered, analytically determined	21	0.81	2.1	2.8	5.2	40.0
	Aluminum	22	--	--	--	--	<100
	Antimony	24	--	--	--	--	<1.0
	Arsenic	24	--	2.3	3.2	4.5	10.0
	Barium	24	81.0	101	130	156	250
	Beryllium	24	--	--	--	--	<1.0
	Boron	32	10.0	26.8	41.0	62.6	180
	Cadmium	24	--	--	--	--	<0.5
	Chromium	24	--	--	--	--	<50.0
	Cobalt	22	--	--	--	--	<2.0
	Copper	24	--	--	--	--	<10.0
	Iron	25	--	--	--	--	<100
	Iron, unfiltered	32	--	5.9	23.6	94.1	4,860
	Lead	24	<1.0	--	--	--	2.0
	Lithium	1	16.9	--	--	--	--
	Manganese	23	<0.4	--	--	--	50.0
	Manganese, unfiltered	26	--	0.01	0.11	0.93	107
	Mercury	1	<0.2	--	--	--	--
	Molybdenum	22	1.8	5.3	7.4	8.9	16.0
	Nickel	24	--	--	--	--	<20.0
	Selenium	24	0.70	0.87	1.4	2.3	11.0
	Strontium	22	200	270	290	640	1,900
	Vanadium	22	--	6.2	7.7	9.7	15.4
	Zinc	23	--	--	--	--	<50.0
	Gross alpha radioactivity, in pCi/L	11	9.4	14.1	21.0	26.0	31.6
	Gross beta radioactivity, in pCi/L	5	5.3	12.9	15.4	16.0	16.6

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Arikaree aquifer —Continued	Radium-226, in pCi/L	11	--	--	--	--	<1.0
	Radium-228, in pCi/L	11	0.08	0.13	0.23	0.38	0.70
	Radon-222, in pCi/L	4	430	501	703	895	955
	Uranium	5	11.0	13.0	23.2	36.9	41.7
White River hydrogeologic unit	pH (standard units)	5	7.4	7.7	7.7	8.0	8.0
	Specific conductance (µS/cm)	5	536	553	670	720	746
	Hardness (as $CaCO_3$)	5	8.0	17.0	22.0	80.0	190
	Calcium	5	3.2	6.5	8.5	26.0	73.0
	Magnesium	4	0.20	0.20	1.6	3.3	3.6
	Potassium	5	3.4	9.6	10.0	11.0	26.0
	Sodium	5	62.0	121	124	131	167
	Sodium adsorption ratio (unitless)	5	1.9	6.0	11.0	18.0	20.0
	Alkalinity (as $CaCO_3$)	5	220	252	261	295	317
	Chloride	5	9.8	11.0	12.0	33.0	57.0
	Fluoride	5	0.40	0.60	1.2	1.9	5.0
	Silica	5	9.2	31.0	49.0	54.0	60.0
	Sulfate	5	2.0	25.0	25.0	40.0	44.0
	Total dissolved solids	5	320	387	428	479	495
	Nitrate (as N)	5	0.02	0.09	0.88	2.3	5.0
	Boron	5	60.0	80.0	120	280	370
	Iron, unfiltered	5	10.0	60.0	110	3,300	5,700
Wasatch aquifer (lower Tertiary aquifer system in Powder River structural basin)	Dissolved oxygen	19	0.01	0.10	0.40	1.0	1.5
	pH (standard units)	215	5.6	7.3	7.6	8.1	9.6
	Specific conductance (µS/cm)	214	248	990	1,635	2,210	7,660
	Hardness (as $CaCO_3$)	216	4.0	130	350	715	4,800
	Calcium	221	1.1	34.0	96.0	190	830
	Magnesium	220	0.33	9.7	26.0	55.0	919
	Potassium	219	0.90	2.9	6.8	11.0	120
	Sodium	221	2.3	110	220	330	1,140
	Sodium adsorption ratio (unitless)	221	0.09	2.3	6.6	9.9	99.4
	Alkalinity (as $CaCO_3$)	221	14.0	180	300	599	1,750
	Chloride	220	0.30	5.2	9.7	16.0	550
	Fluoride	203	0.10	0.20	0.30	0.70	7.6
	Silica	209	1.0	8.6	11.0	17.3	43.0

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Wasatch aquifer (lower Tertiary aquifer system in Powder River structural basin)—Continued	Sulfate	220	0.50	110	420	883	5,940
	Total dissolved solids	220	160	624	1,125	1,700	8,620
	Ammonia (as N)	85	0.04	0.54	1.0	2.6	130
	Ammonia plus organic nitrogen (as N)	14	0.11	0.71	1.3	7.4	30.0
	Ammonia plus organic nitrogen, unfiltered (as N)	6	0.13	0.23	0.42	0.73	1.1
	Ammonia, unfiltered (as N)	20	0.02	0.20	1.1	1.8	9.1
	Dissolved organic carbon	80	0.80	2.2	7.5	33.0	280
	Nitrate (as N)	107	0.01	0.02	0.08	0.38	19.4
	Nitrate plus nitrite (as N)	81	0.01	0.01	0.04	0.12	28.0
	Nitrate, unfiltered (as N)	14	--	--	--	--	<0.005
	Nitrate+nitrite, unfiltered (as N)	6	--	0.04	0.07	0.10	0.30
	Nitrite (as N)	37	--	0.005	0.01	0.02	0.11
	Nitrite, unfiltered (as N)	15	--	--	--	--	<0.01
	Organic nitrogen	12	0.09	0.16	0.48	1.1	4.0
	Organic nitrogen, unfiltered	21	--	0.006	0.02	0.07	1.1
	Orthophosphate (as P)	21	0.01	0.02	0.02	0.03	0.06
	Phosphorus	16	0.003	0.01	0.03	0.04	6.0
	Phosphorus, unfiltered	6	0.01	0.02	0.04	0.51	1.8
	Total nitrogen	14	0.38	0.53	1.6	7.5	30.0
	Total nitrogen, unfiltered	6	0.18	0.23	0.45	0.73	1.4
	Total nitrogen, unfiltered, analytically determined	18	0.25	0.68	1.5	2.0	9.1
	Aluminum	55	10.0	10.3	20.7	41.8	2,000
	Antimony	31	--	0.29	0.40	0.53	1.0
	Arsenic	85	--	0.56	1.2	2.4	36.0
	Barium	63	6.7	25.8	64.7	200	1,400
	Beryllium	40	<1.0	--	--	--	20.0
	Boron	181	10.0	38.5	84.1	184	4,400
	Cadmium	51	--	0.005	0.03	0.18	9.0
	Chromium	47	--	2.6	4.8	8.8	20.0
	Cobalt	20	--	--	--	--	<100
	Copper	37	0.30	0.58	1.2	2.7	28.0
	Iron	112	1.0	101	555	2,050	110,000
	Iron, unfiltered	139	10.0	90.0	380	2,200	46,000
	Lead	47	--	0.10	0.43	1.9	22.0
	Lithium	48	10.6	80.0	100	135	700

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Wasatch aquifer (lower Tertiary aquifer system in Powder River structural basin)—Continued	Manganese	79	4.0	30.0	120	320	4,800
	Manganese, unfiltered	24	5.8	19.7	60.4	139	4,700
	Mercury	31	--	0.03	0.06	0.11	0.40
	Molybdenum	32	--	1.6	3.4	7.2	44.0
	Nickel	42	0.44	0.56	1.9	6.5	300
	Selenium	54	--	0.04	0.23	1.4	330
	Strontium	26	8.1	143	805	3,450	13,000
	Vanadium	21	0.30	0.48	1.1	2.7	15.0
	Zinc	69	--	2.7	10.3	38.6	17,000
	Gross alpha radioactivity, in pCi/L	14	1.1	1.8	5.4	15.4	55.0
	Gross beta radioactivity, in pCi/L	21	2.1	3.1	5.3	9.0	29.0
	Radium-226, in pCi/L	15	0.10	0.26	0.50	0.94	9.9
	Radium-228, in pCi/L	2	<1.0	--	--	--	2.0
	Radon-222, in pCi/L	6	490	540	570	730	1,390
	Tritium, unfiltered, in pCi/L	8	--	1.0	1.6	7.6	179
	Uranium	39	--	0.03	0.30	7.2	84.0
Wasatch Formation coal aquifers (lower Tertiary aquifer system in Powder River structural basin)	pH (standard units)	6	7.9	8.0	8.0	8.1	8.2
	Specific conductance (µS/cm)	2	1,480	1,480	1,600	1,720	1,720
	Calcium	8	15.0	20.7	34.0	131	448
	Magnesium	8	3.2	4.8	7.4	45.0	292
	Potassium	6	3.1	4.2	4.9	6.0	8.0
	Sodium	8	142	225	312	396	560
	Sodium adsorption ratio (unitless)	8	2.3	5.5	12.8	16.9	21.9
	Alkalinity (as $CaCO_3$)	2	550	550	560	570	570
	Bicarbonate	6	317	378	678	1,060	1,250
	Fluoride	2	0.40	--	--	--	1.0
	Chloride	8	2.0	5.4	9.0	12.8	44.0
	Silica	2	8.2	8.2	9.6	11.0	11.0
	Sulfate	6	5.4	20.7	339	720	3,040
	Total dissolved solids	8	805	881	1,095	1,237	4,582
	Boron	1	70.0	--	--	--	--
	Barium	1	500	--	--	--	--
	Iron	3	300	--	400	--	10,300
	Zinc	1	30.0	--	--	--	--
	Radium-226, in pCi/L	1	2.2	--	--	--	--

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Fort Union aquifer (lower Tertiary aquifer system in the Powder River structural basin)	Dissolved oxygen	18	0.02	0.10	0.25	5.2	11.8
	pH (standard units)	233	6.4	7.4	7.9	8.3	8.9
	Specific conductance (µS/cm)	196	217	768	1,380	1,995	6,000
	Hardness (as $CaCO_3$)	227	6.0	32.0	140	480	2,740
	Calcium	238	1.8	8.9	31.0	100	600
	Magnesium	238	0.10	2.8	11.5	47.0	346
	Potassium	222	0.20	3.6	6.4	11.0	150
	Sodium	238	2.7	140	274	385	890
	Sodium adsorption ratio (unitless)	238	0.10	5.2	8.5	20.9	57.0
	Alkalinity (as $CaCO_3$)	237	77.0	283	445	670	1,943
	Chloride	238	1.0	5.8	8.1	15.8	140
	Fluoride	191	0.10	0.50	0.87	1.6	8.1
	Silica	216	1.2	8.0	9.3	13.0	86.6
	Sulfate	236	0.20	8.6	142	690	3,560
	Total dissolved solids	236	113	537	1,015	1,550	5,480
	Ammonia (as N)	17	0.01	0.67	1.3	2.5	43.0
	Ammonia plus organic nitrogen (as N)	10	0.37	0.97	1.6	2.6	37.0
	Ammonia plus organic nitrogen, unfiltered (as N)	32	0.05	0.28	0.91	3.2	130
	Ammonia, unfiltered (as N)	40	0.01	0.49	1.0	1.7	4.6
	Dissolved organic carbon	13	1.0	1.5	2.0	2.3	128
	Nitrate (as N)	86	--	0.009	0.04	0.27	2.3
	Nitrate plus nitrite (as N)	55	--	0.01	0.04	0.13	13.0
	Nitrate, unfiltered (as N)	7	<0.005	--	--	--	0.12
	Nitrate+nitrite, unfiltered (as N)	34	0.01	0.02	0.07	0.52	13.0
	Nitrite (as N)	20	--	0.001	0.003	0.007	0.03
	Nitrite, unfiltered (as N)	7	<0.005	--	--	--	0.03
	Organic nitrogen	5	0.39	0.40	0.43	3.0	6.0
	Organic nitrogen, unfiltered	37	0.02	0.05	0.23	0.84	130
	Orthophosphate (as P)	14	0.01	0.01	0.03	0.04	0.08
	Phosphorus	4	--	0.009	0.01	0.02	0.03
	Phosphorus, unfiltered	35	0.01	0.01	0.04	0.10	6.3
	Total nitrogen	10	0.39	0.79	2.1	2.7	37.0
	Total nitrogen, unfiltered	32	0.05	0.71	1.3	4.1	130
	Total nitrogen, unfiltered, analytically determined	12	0.59	1.0	1.5	2.0	2.8

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Fort Union aquifer (lower Tertiary aquifer system in the Powder River structural basin)—Continued	Aluminum	50	10.0	15.5	28.1	51.1	280
	Antimony	55	--	0.26	0.44	0.72	2.0
	Arsenic	80	--	0.16	0.48	1.5	150
	Barium	43	6.1	30.3	100	200	550
	Beryllium	63	--	0.005	0.05	0.56	20.0
	Boron	153	10.0	46.4	92.7	140	5,400
	Cadmium	76	--	0.01	0.06	0.32	20.0
	Chromium	57	--	--	--	--	<50.0
	Cobalt	13	--	--	--	--	<100
	Copper	62	--	0.53	1.6	4.7	230
	Iron	120	0.02	58.5	170	645	120,000
	Iron, unfiltered	140	1.0	105	308	855	900,000
	Lead	86	--	0.31	1.1	3.6	100
	Lithium	35	20.0	20.0	60.0	130	900
	Manganese	72	2.0	14.4	30.0	69.0	1,400
	Manganese, unfiltered	44	4.6	30.0	68.7	475	15,000
	Mercury	64	--	--	--	--	<1.0
	Molybdenum	65	--	0.46	1.2	3.2	26.0
	Nickel	52	2.0	2.1	2.9	4.2	12.0
	Selenium	80	--	0.06	0.20	0.66	20.0
	Strontium	19	18.0	180	498	2,500	9,100
	Vanadium	27	0.10	0.33	0.88	2.3	64.0
	Zinc	56	2.0	3.3	11.4	39.2	1,800
	Gross alpha radioactivity, in pCi/L	21	--	0.98	1.5	2.3	5.2
	Gross beta radioactivity, in pCi/L	19	--	2.2	4.8	11.0	24.0
	Radium-226, in pCi/L	14	0.12	0.30	0.57	0.60	4.8
	Radium-228, in pCi/L	8	--	1.0	1.5	5.5	6.7
	Radon-222, in pCi/L	2	180	--	--	--	340
	Tritium, unfiltered, in pCi/L	2	<1.0	--	--	--	76.2
	Uranium	29	0.02	0.03	0.13	0.53	19.0

Appendix E-1. Summary statistics for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituents	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Fort Union Formation coal aquifers (lower Tertiary aquifer system in the Powder River structural basin)	pH (standard units)	217	6.8	7.3	7.7	8.0	9.2
	Specific conductance (µS/cm)	62	470	990	1,205	1,700	4,180
	Calcium	447	1.7	16.0	26.0	38.0	160
	Magnesium	448	0.02	7.2	12.1	19.0	67.0
	Potassium	222	2.2	7.0	10.0	15.3	50.4
	Sodium	449	12.0	201	314	528	1,500
	Sodium adsorption ratio (unitless)	449	0.24	6.9	10.8	22.2	133
	Alkalinity (as $CaCO_3$)	318	67.5	514	819	1,240	3,419
	Bicarbonate	136	329	928	1,300	1,630	4,270
	Carbonate	26	1.0	1.0	9.9	16.8	349
	Chloride	438	2.0	8.9	11.8	18.0	583
	Fluoride	132	0.10	0.80	1.1	1.5	4.6
	Silica	83	0.20	4.2	4.8	6.5	22.0
	Sulfate	245	0.01	0.50	2.0	5.0	986
	Total dissolved solids	442	96.9	734	1,090	1,569	4,589
	Arsenic	51	--	0.06	0.27	0.63	510
	Boron	44	--	56.5	75.1	100	300
	Barium	121	10.0	330	550	800	600,000
	Cobalt	41	--	0.07	0.09	0.10	0.24
	Chromium	51	--	0.002	0.03	0.64	2,000
	Copper	45	1.0	2.8	3.8	6.1	28.6
	Iron	154	9.5	150	420	810	120,000
	Lithium	52	18.0	35.5	49.5	68.5	208
	Manganese	45	5.3	14.0	30.0	47.0	130
	Nickel	45	0.77	2.6	4.6	8.1	35.4
	Strontium	116	25.5	187	436	743	1,900
	Zinc	58	--	0.98	3.1	10.0	554
	Radium-226, in pCi/L	33	0.30	0.40	0.68	1.5	2.7

Appendix E-2

Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the NERB excluding Wind River structural basin, Wyoming

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Lance aquifer (Upper Cretaceous aquifer system in Powder River structural basin)	Dissolved oxygen	8	0.10	0.10	0.55	0.90	4.5
	pH (standard units)	46	7.0	7.6	8.0	8.4	8.9
	Specific conductance (µS/cm)	48	412	1,020	1,435	2,065	3,940
	Hardness (as $CaCO_3$)	47	5.0	20.0	71.5	360	1,700
	Calcium	48	1.0	5.7	13.0	88.0	481
	Magnesium	48	0.20	1.6	7.1	30.5	134
	Potassium	47	0.80	2.0	3.1	4.8	12.0
	Sodium	48	8.5	190	291	431	922
	Sodium adsorption ratio (unitless)	48	0.26	3.4	16.0	35.5	94.0
	Alkalinity (as $CaCO_3$)	48	131	355	448	522	1,123
	Chloride	48	1.6	4.4	8.6	19.0	110
	Fluoride	47	0.01	0.20	0.50	1.4	9.4
	Silica	46	2.1	8.2	10.0	13.0	29.0
	Sulfate	48	0.30	140	273	582	1,780
	Total dissolved solids	47	244	662	946	1,370	3,060
	Ammonia (as N)	7	--	0.04	0.38	0.56	0.95
	Ammonia, unfiltered (as N)	1	<0.03	--	--	--	--
	Dissolved organic carbon	8	0.72	1.1	1.6	2.7	3.3
	Nitrate (as N)	23	--	0.008	0.04	0.14	3.6
	Nitrate plus nitrite (as N)	11	0.01	0.05	0.14	1.2	2.9
	Nitrate, unfiltered (as N)	1	0.71	--	--	--	--
	Nitrite (as N)	7	<0.005	--	--	--	0.006
	Nitrite, unfiltered (as N)	1	0.006	--	--	--	--
	Organic nitrogen, unfiltered	7	--	--	--	--	<0.39
	Orthophosphate (as P)	7	0.03	0.05	0.05	0.06	0.06
	Phosphorus	1	0.03	--	--	--	--
	Phosphorus, unfiltered	1	<0.03	--	--	--	--
	Total nitrogen, unfiltered, analytically determined	8	0.15	0.52	0.74	1.1	2.8
	Aluminum	10	--	--	--	--	<100
	Antimony	8	--	--	--	--	<1.0
	Arsenic	12	--	0.42	0.85	1.7	7.5
	Barium	10	10.0	14.7	22.2	33.3	68.0
	Beryllium	10	--	--	--	--	<10.0
	Boron	44	40.0	120	160	220	3,700
	Cadmium	11	--	--	--	--	<10.0
	Chromium	11	--	--	--	--	<50.0
	Cobalt	8	--	--	--	--	<2.0
	Copper	10	--	--	--	--	<10.0
	Iron	14	0.007	0.43	5.5	120	1,400

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Lance aquifer (Upper Cretaceous aquifer system in Powder River structural basin)—Continued	Iron, unfiltered	38	10.0	47.5	110	330	8,600
	Lead	11	--	--	--	--	<50.0
	Lithium	1	7.0	--	--	--	--
	Manganese	11	5.4	5.7	12.0	50.0	270
	Manganese, unfiltered	9	4.3	11.6	23.0	120	290
	Mercury	4	<1.0	--	--	--	1.5
	Molybdenum	9	5.4	5.7	7.2	9.0	13.0
	Nickel	10	--	--	--	--	<100
	Selenium	10	--	0.68	1.4	2.9	8.2
	Strontium	8	98.0	130	630	2,900	4,800
	Vanadium	9	<10.0	--	--	--	10.0
	Zinc	11	10.0	14.4	22.5	35.1	60.0
	Gross alpha radioactivity, in pCi/L	1	9.5	--	--	--	--
	Gross beta radioactivity, in pCi/L	1	<7.1	--	--	--	--
	Radium-226, in pCi/L	1	0.15	--	--	--	--
	Uranium	6	--	0.12	0.84	44.0	47.0
Fox Hills aquifer (Upper Cretaceous aquifer system in Powder River structural basin)	Dissolved oxygen	1	0.01	--	--	--	--
	pH (standard units)	21	7.2	7.7	8.2	8.5	9.3
	Specific conductance (µS/cm)	21	875	1,450	1,730	2,780	4,690
	Hardness (as $CaCO_3$)	18	5.0	12.0	51.0	164	320
	Calcium	21	1.8	5.0	20.0	46.0	69.0
	Magnesium	21	0.10	1.1	6.4	16.0	37.0
	Potassium	21	0.11	1.3	3.3	4.2	10.0
	Sodium	21	82.0	315	391	625	1,100
	Sodium adsorption ratio (unitless)	21	0.10	8.2	24.0	39.0	66.0
	Alkalinity (as $CaCO_3$)	21	251	311	401	520	816
	Chloride	21	2.1	11.0	13.0	29.0	89.0
	Fluoride	21	0.10	0.28	0.40	0.80	7.0
	Silica	18	3.2	8.6	10.5	12.0	15.0
	Sulfate	21	3.3	210	460	840	2,400
	Total dissolved solids	21	28.0	904	1,170	2,000	3,520
	Ammonia (as N)	1	0.83	--	--	--	--
	Dissolved organic carbon	1	1.2	--	--	--	--
	Nitrate (as N)	7	--	0.01	0.04	0.11	0.98
	Nitrate plus nitrite (as N)	5	0.20	0.33	0.90	1.3	3.4
	Nitrite (as N)	2	0.02	--	--	--	0.03
	Orthophosphate (as P)	1	0.04	--	--	--	--
	Phosphorus, unfiltered	2	<0.03	--	--	--	0.05

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Fox Hills aquifer (Upper Cretaceous aquifer system in Powder River structural basin)—Continued	Total nitrogen, unfiltered, analytically determined	1	1.8	--	--	--	--
	Aluminum	1	<100	--	--	--	--
	Antimony	2	--	--	--	--	<1.0
	Arsenic	5	--	--	--	--	<10.0
	Barium	5	--	--	--	--	<100
	Beryllium	2	--	--	--	--	<1.0
	Boron	16	0.03	115	315	480	1,300
	Cadmium	5	--	--	--	--	<10.0
	Chromium	5	--	--	--	--	<50.0
	Cobalt	1	<2.0	--	--	--	--
	Copper	2	--	--	--	--	<5.0
	Iron	3	<100	--	--	--	940
	Iron, unfiltered	12	30.0	65.5	162	291	4,900
	Lead	5	--	--	--	--	<50.0
	Manganese	2	30.0	--	--	--	41.0
	Manganese, unfiltered	1	44.0	--	--	--	--
	Mercury	4	--	--	--	--	<1.0
	Molybdenum	1	<5.0	--	--	--	--
	Nickel	2	--	--	--	--	<20.0
	Selenium	7	--	1.1	2.6	6.4	20.0
	Strontium	1	1,500	--	--	--	--
	Vanadium	1	20.0	--	--	--	--
	Zinc	2	--	--	--	--	<50.0
	Gross alpha radioactivity, in pCi/L	1	3.4	--	--	--	--
	Gross beta radioactivity, in pCi/L	1	4.1	--	--	--	--
	Radium-226, in pCi/L	1	<0.2	--	--	--	--
	Radium-228, in pCi/L	1	2.7	--	--	--	--
	Uranium	5	--	0.45	3.0	20.0	21.0
Lewis confining unit	pH (standard units)	1	7.9	--	--	--	--
	Specific conductance (µS/cm)	1	1,110	--	--	--	--
	Hardness (as $CaCO_3$)	1	52.0	--	--	--	--
	Calcium	1	16.0	--	--	--	--
	Magnesium	1	2.9	--	--	--	--
	Potassium	1	0.10	--	--	--	--
	Sodium	1	236	--	--	--	--
	Sodium adsorption ratio (unitless)	1	14.3	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	276	--	--	--	--

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Lewis confining unit —Continued	Chloride	1	30.0	--	--	--	--
	Fluoride	1	0.20	--	--	--	--
	Silica	1	38.0	--	--	--	--
	Sulfate	1	233	--	--	--	--
	Total dissolved solids	1	739	--	--	--	--
	Boron	1	60.0	--	--	--	--
	Iron, unfiltered	1	440	--	--	--	--
Pierre confining unit	pH (standard units)	4	7.4	7.5	7.8	8.2	8.4
	Specific conductance (µS/cm)	4	490	678	908	1,575	2,200
	Hardness (as $CaCO_3$)	4	16.0	88.0	190	290	360
	Calcium	4	3.9	19.5	48.0	71.0	81.0
	Magnesium	4	1.5	9.8	18.0	28.0	38.0
	Potassium	4	2.6	3.2	5.6	9.2	11.0
	Sodium	4	41.0	46.5	87.5	342	560
	Sodium adsorption ratio (unitless)	4	1.2	1.3	2.5	32.3	61.0
	Alkalinity (as $CaCO_3$)	4	188	235	286	532	773
	Chloride	4	1.7	1.8	3.9	10.5	15.0
	Fluoride	4	0.20	0.30	0.45	0.60	0.70
	Silica	4	6.9	11.0	15.5	22.5	29.0
	Sulfate	4	65.0	124	193	332	460
	Total dissolved solids	4	276	407	591	1,077	1,510
	Nitrate (as N)	2	0.09	--	--	--	0.16
	Nitrate plus nitrite (as N)	1	0.51	--	--	--	--
	Boron	3	20.0	--	30.0	--	140
	Iron, unfiltered	4	10.0	25.0	95.0	250	350
Mesaverde aquifer	pH (standard units)	7	6.7	7.5	7.8	8.3	8.9
	Specific conductance (µS/cm)	7	625	823	1,950	3,120	5,000
	Hardness (as $CaCO_3$)	7	10.0	44.0	210	410	550
	Calcium	7	0.20	15.0	62.0	97.0	146
	Magnesium	7	1.2	2.3	14.0	46.0	48.0
	Potassium	7	0.80	2.0	2.3	7.4	9.2
	Sodium	7	29.0	141	366	712	1,100
	Sodium adsorption ratio (unitless)	7	0.63	6.7	19.0	22.8	48.0
	Alkalinity (as $CaCO_3$)	7	33.0	180	270	349	543
	Chloride	7	1.6	3.7	12.0	36.0	73.0
	Fluoride	7	0.20	0.30	0.30	0.90	2.5
	Silica	7	1.8	7.1	10.0	13.0	22.0

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Mesaverde aquifer —Continued	Sulfate	7	89.0	186	995	1,430	2,040
	Total dissolved solids	7	370	550	1,490	2,340	4,430
	Nitrate (as N)	4	0.02	0.02	0.29	0.77	0.97
	Nitrate plus nitrite (as N)	2	0.10	--	--	--	153
	Boron	7	80.0	80.0	150	420	480
	Iron, unfiltered	7	110	220	1,300	12,000	20,000
Cody confining unit	pH (standard units)	1	8.0	--	--	--	--
	Specific conductance (µS/cm)	2	1,130	--	--	--	13,000
	Hardness (as $CaCO_3$)	2	600	--	--	--	3,100
	Calcium	2	77.0	--	--	--	298
	Magnesium	2	99.0	--	--	--	573
	Potassium	1	17.0	--	--	--	--
	Sodium	2	30.0	--	--	--	2,350
	Sodium adsorption ratio (unitless)	2	0.53	--	--	--	18.4
	Alkalinity (as $CaCO_3$)	2	167	--	--	--	410
	Chloride	2	8.0	--	--	--	227
	Sulfate	2	465	--	--	--	7,830
	Total dissolved solids	2	780	--	--	--	12,600
	Nitrate (as N)	2	0.23	--	--	--	0.36
	Boron	1	2,000	--	--	--	--
Frontier aquifer	pH (standard units)	11	7.1	7.8	8.7	8.9	8.9
	Specific conductance (µS/cm)	13	556	1,180	1,550	2,350	3,230
	Hardness (as $CaCO_3$)	12	3.0	10.0	205	430	730
	Calcium	13	0.10	1.4	47.0	110	177
	Magnesium	12	0.10	1.2	19.0	32.0	70.0
	Potassium	9	0.60	1.2	1.7	4.7	6.2
	Sodium	14	12.0	120	326	550	766
	Sodium adsorption ratio (unitless)	13	0.07	2.4	4.0	63.7	100
	Alkalinity (as $CaCO_3$)	14	143	230	322	570	1,170
	Chloride	14	1.7	4.6	9.1	21.0	190
	Fluoride	11	0.30	0.70	0.90	1.5	5.5
	Silica	9	7.4	9.8	11.0	15.0	29.0
	Sulfate	14	4.3	104	328	528	1,280
	Total dissolved solids	12	348	887	1,120	1,725	2,270
	Nitrate (as N)	4	--	0.02	0.03	0.07	0.09
	Nitrate plus nitrite (as N)	6	--	0.10	0.40	1.2	3.3
	Phosphorus, unfiltered	1	<0.03	--	--	--	--

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Frontier aquifer—Continued	Boron	7	270	370	580	1,500	1,800
	Iron, unfiltered	9	20.0	57.0	210	380	2,900
Mowry confining unit	pH (standard units)	1	7.3	--	--	--	--
	Specific conductance (µS/cm)	1	1,140	--	--	--	--
	Hardness (as $CaCO_3$)	1	130	--	--	--	--
	Calcium	1	36.0	--	--	--	--
	Magnesium	1	9.7	--	--	--	--
	Potassium	1	1.7	--	--	--	--
	Sodium	1	196	--	--	--	--
	Sodium adsorption ratio (unitless)	1	7.5	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	116	--	--	--	--
	Chloride	1	1.9	--	--	--	--
	Fluoride	1	1.3	--	--	--	--
	Silica	1	22.0	--	--	--	--
	Sulfate	1	424	--	--	--	--
	Total dissolved solids	1	765	--	--	--	--
	Ammonia (as N)	2	0.23	--	--	--	0.83
	Nitrate (as N)	2	0.04	--	--	--	0.07
	Nitrate plus nitrite (as N)	3	0.04	--	0.07	--	0.50
	Nitrite (as N)	2	--	--	--	--	<0.008
	Orthophosphate (as P)	2	<0.02	--	--	--	0.12
	Boron	1	370	--	--	--	--
	Iron, unfiltered	1	620	--	--	--	--
Muddy aquifer	pH (standard units)	1	8.5	--	--	--	--
	Specific conductance (µS/cm)	1	3,640	--	--	--	--
	Hardness (as $CaCO_3$)	1	16.0	--	--	--	--
	Calcium	1	0.40	--	--	--	--
	Magnesium	1	3.5	--	--	--	--
	Potassium	1	9.5	--	--	--	--
	Sodium	1	1,000	--	--	--	--
	Sodium adsorption ratio (unitless)	1	110	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	1,607	--	--	--	--
	Chloride	1	270	--	--	--	--
	Fluoride	1	4.3	--	--	--	--
	Silica	1	12.0	--	--	--	--
	Total dissolved solids	1	2,380	--	--	--	--
	Boron	1	1,200	--	--	--	--

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Newcastle aquifer	pH (standard units)	1	7.7	--	--	--	--
	Hardness (as $CaCO_3$)	1	214	--	--	--	--
	Calcium	1	51.0	--	--	--	--
	Magnesium	1	21.0	--	--	--	--
	Sodium	1	3,410	--	--	--	--
	Sodium adsorption ratio (unitless)	1	102	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	1,451	--	--	--	--
	Chloride	1	4,380	--	--	--	--
	Sulfate	1	5.0	--	--	--	--
	Total dissolved solids	1	8,740	--	--	--	--
	Boron	1	5,100	--	--	--	--
Skull Creek confining unit	Ammonia (as N)	1	5.6	--	--	--	--
	Nitrate (as N)	1	<0.06	--	--	--	--
	Nitrate plus nitrite (as N)	1	<0.06	--	--	--	--
	Nitrite (as N)	1	<0.008	--	--	--	--
	Orthophosphate (as P)	1	<0.02	--	--	--	--
Cloverly aquifer	pH (standard units)	5	8.0	8.2	8.2	8.5	9.1
	Specific conductance (µS/cm)	5	1,620	1,910	2,490	4,510	4,850
	Hardness (as $CaCO_3$)	5	6.5	12.0	21.0	30.0	40.0
	Calcium	5	1.0	1.7	3.4	5.6	12.0
	Magnesium	5	1.0	1.9	2.2	3.0	4.0
	Potassium	5	1.0	2.0	3.9	5.4	12.0
	Sodium	5	340	435	615	1,180	1,260
	Sodium adsorption ratio (unitless)	5	24.0	73.6	77.0	93.1	120
	Alkalinity (as $CaCO_3$)	5	210	536	700	1,041	2,008
	Chloride	5	21.0	117	203	278	1,080
	Fluoride	4	0.60	1.4	2.5	3.0	3.2
	Silica	4	12.0	12.0	12.0	12.0	12.0
	Sulfate	4	1.0	171	451	563	565
	Total dissolved solids	5	1,080	1,120	1,670	2,790	2,970
	Nitrate (as N)	4	--	--	--	--	<0.09
	Nitrate plus nitrite (as N)	1	<0.1	--	--	--	--
	Boron	4	60.0	420	2,190	3,700	3,800
	Iron, unfiltered	4	20.0	21.8	28.3	70.0	110

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Inyan Kara aquifer	Dissolved oxygen	1	0.17	--	--	--	--
	pH (standard units)	50	4.2	7.5	7.7	8.2	9.0
	Specific conductance (µS/cm)	49	309	696	1,350	1,780	4,000
	Hardness (as $CaCO_3$)	41	3.0	57.0	200	480	2,100
	Calcium	52	0.04	7.8	40.5	84.0	603
	Magnesium	49	0.02	2.8	16.0	32.0	240
	Potassium	49	0.04	2.4	6.0	11.0	36.0
	Sodium	59	2.6	61.0	232	365	810
	Sodium adsorption ratio (unitless)	49	0.10	1.2	2.3	16.0	190
	Alkalinity (as $CaCO_3$)	59	1.0	141	170	223	387
	Chloride	59	1.7	5.0	12.0	19.0	840
	Fluoride	46	0.03	0.20	0.40	0.60	2.8
	Silica	42	4.0	8.2	10.0	13.0	39.0
	Sulfate	59	1.0	220	454	830	2,100
	Total dissolved solids	58	180	634	912	1,480	3,340
	Ammonia (as N)	1	<0.025	--	--	--	--
	Nitrate (as N)	14	--	0.008	0.03	0.10	4.5
	Nitrate plus nitrite (as N)	15	0.01	0.02	0.08	0.39	1.6
	Nitrite (as N)	2	--	--	--	--	<0.1
	Organic nitrogen, unfiltered	1	<0.2	--	--	--	--
	Orthophosphate (as P)	1	0.09	--	--	--	--
	Phosphorus, unfiltered	1	<0.03	--	--	--	--
	Total nitrogen, unfiltered, analytically determined	1	0.20	--	--	--	--
	Aluminum	1	<100	--	--	--	--
	Antimony	1	<0.5	--	--	--	--
	Arsenic	8	<1.0	--	--	--	33.0
	Barium	7	<50.0	--	--	--	300
	Beryllium	1	<1.0	--	--	--	--
	Boron	37	10.0	60.0	70.0	210	1,200
	Cadmium	7	--	--	--	--	<10.0
	Chromium	7	--	--	--	--	<50.0
	Cobalt	1	<2.0	--	--	--	--
	Copper	2	--	--	--	--	<10.0
	Iron	9	20.0	140	840	6,000	18,000
	Iron, unfiltered	29	10.0	180	530	2,000	46,000
	Lead	7	--	--	--	--	<50.0
	Manganese	2	30.0	--	--	--	180
	Manganese, unfiltered	2	<10.0	--	--	--	180
	Mercury	6	--	--	--	--	<1.0
	Molybdenum	1	6.3	--	--	--	--

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Inyan Kara aquifer —Continued	Nickel	1	<4.0	--	--	--	--
	Selenium	7	<1.0	--	--	--	20.0
	Strontium	1	1,400	--	--	--	--
	Vanadium	1	<10.0	--	--	--	--
	Zinc	1	<50.0	--	--	--	--
	Gross alpha radioactivity, in pCi/L	6	0.80	1.1	2.4	6.2	7.6
	Gross beta radioactivity, in pCi/L	2	3.7	--	--	--	7.2
	Radium-226, in pCi/L	5	0.75	1.2	1.3	2.8	6.9
	Radium-228, in pCi/L	5	0.22	0.50	0.60	1.3	2.1
	Uranium	9	--	0.39	6.0	15.0	23.0
Morrison confining unit	pH (standard units)	1	8.2	--	--	--	--
	Specific conductance (µS/cm)	1	1,400	--	--	--	--
	Hardness (as $CaCO_3$)	1	99.0	--	--	--	--
	Calcium	1	23.0	--	--	--	--
	Magnesium	1	10.0	--	--	--	--
	Potassium	1	8.7	--	--	--	--
	Sodium	1	276	--	--	--	--
	Sodium adsorption ratio (unitless)	1	12.0	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	205	--	--	--	--
	Chloride	1	6.0	--	--	--	--
	Fluoride	1	0.80	--	--	--	--
	Silica	1	9.2	--	--	--	--
	Sulfate	1	460	--	--	--	--
	Total dissolved solids	1	922	--	--	--	--
	Nitrate (as N)	1	0.18	--	--	--	--
	Boron	1	1,800	--	--	--	--
	Iron, unfiltered	1	320	--	--	--	--
Sundance aquifer	Dissolved oxygen	4	0.10	1.1	2.2	5.7	9.0
	pH (standard units)	15	5.6	7.2	7.5	7.7	8.1
	Specific conductance (µS/cm)	15	425	779	1,200	2,040	4,970
	Hardness (as $CaCO_3$)	12	140	320	501	788	1,300
	Calcium	15	35.0	56.0	105	140	393
	Magnesium	15	14.0	20.0	52.0	87.0	112
	Potassium	14	2.5	6.0	8.3	12.0	18.0
	Sodium	15	5.0	9.0	24.0	110	1,150
	Sodium adsorption ratio (unitless)	15	0.10	0.19	0.40	2.2	26.7

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Sundance aquifer —Continued	Alkalinity (as $CaCO_3$)	15	6.6	194	290	339	407
	Chloride	15	1.3	3.9	6.8	9.6	19.0
	Fluoride	13	0.02	0.20	0.20	0.30	1.4
	Silica	12	1.7	9.3	12.5	14.0	16.0
	Sulfate	15	35.0	156	420	927	2,750
	Total dissolved solids	15	243	492	847	1,690	4,100
	Ammonia (as N)	4	--	--	--	--	<0.25
	Dissolved organic carbon	3	0.33	--	1.2	--	1.4
	Nitrate (as N)	6	0.03	0.09	1.7	2.7	2.8
	Nitrate plus nitrite (as N)	3	0.04	--	0.33	--	8.9
	Nitrite (as N)	4	--	--	--	--	<0.005
	Organic nitrogen, unfiltered	4	--	--	--	--	<2.9
	Orthophosphate (as P)	4	0.03	0.03	0.04	0.06	0.06
	Total nitrogen, unfiltered, analytically determined	4	--	0.81	1.6	2.4	2.9
	Aluminum	4	--	--	--	--	<100
	Antimony	4	--	--	--	--	<1.0
	Arsenic	5	--	--	--	--	<4.0
	Barium	4	8.7	13.9	19.0	32.0	45.0
	Beryllium	4	--	--	--	--	<1.0
	Boron	10	60.0	110	170	260	350
	Cadmium	4	--	--	--	--	<0.2
	Chromium	4	--	--	--	--	<5.0
	Cobalt	4	--	--	--	--	<2.0
	Copper	4	<5.0	--	--	--	10.0
	Iron	7	--	26.8	84.3	350	1,060
	Iron, unfiltered	10	--	48.0	221	1,200	5,000
	Lead	4	--	--	--	--	<1.0
	Manganese	4	<2.0	--	--	--	16.0
	Manganese, unfiltered	5	--	1.2	2.4	16.0	160
	Mercury	1	1.1	--	--	--	--
	Molybdenum	4	11.0	12.0	13.0	13.5	14.0
	Nickel	4	--	--	--	--	<4.0
	Selenium	5	1.0	3.0	3.0	9.0	15.0
	Strontium	4	1,800	1,850	2,350	2,950	3,100
	Vanadium	4	--	--	--	--	<10.0
	Zinc	4	--	--	--	--	<50.0
	Gross beta radioactivity, in pCi/L	1	<10.0	--	--	--	--
	Radium-226, in pCi/L	1	0.10	--	--	--	--
	Uranium	1	3.3	--	--	--	--

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Chugwater confining unit	pH (standard units)	2	7.8	--	--	--	7.9
	Specific conductance (µS/cm)	2	1,570	--	--	--	2,380
	Hardness (as $CaCO_3$)	2	750	--	--	--	1,600
	Calcium	2	188	--	--	--	508
	Magnesium	2	67.0	--	--	--	93.0
	Potassium	2	2.5	--	--	--	4.3
	Sodium	2	15.0	--	--	--	108
	Sodium adsorption ratio (unitless)	2	0.16	--	--	--	1.7
	Alkalinity (as $CaCO_3$)	2	139	--	--	--	172
	Chloride	2	5.7	--	--	--	7.7
	Fluoride	2	0.30	--	--	--	0.60
	Silica	2	11.0	--	--	--	26.0
	Sulfate	2	789	--	--	--	1,460
	Total dissolved solids	2	1,300	--	--	--	2,410
	Nitrate (as N)	1	0.84	--	--	--	--
	Nitrate plus nitrite (as N)	1	4.2	--	--	--	--
	Boron	2	170	--	--	--	210
	Iron, unfiltered	2	10.0	--	--	--	60.0
Spearfish aquifer	Dissolved oxygen	4	0.20	0.25	2.1	6.3	8.8
	pH (standard units)	13	6.7	7.0	7.2	7.5	8.1
	Specific conductance (µS/cm)	12	674	2,045	2,620	3,160	41,800
	Hardness (as $CaCO_3$)	12	340	1,555	1,700	1,875	3,000
	Calcium	12	66.0	470	500	542	910
	Magnesium	12	43.0	78.5	103	150	168
	Potassium	11	2.1	5.8	8.5	11.0	24.0
	Sodium	12	13.0	34.5	79.5	125	10,100
	Sodium adsorption ratio (unitless)	12	0.20	0.39	0.80	1.4	81.0
	Alkalinity (as $CaCO_3$)	13	154	192	230	256	336
	Chloride	13	2.5	9.0	13.0	22.0	15,600
	Fluoride	10	0.09	0.10	0.25	0.60	1.0
	Silica	11	10.0	12.0	14.0	17.0	36.0
	Sulfate	13	84.0	1,400	1,600	2,000	3,190
	Total dissolved solids	11	459	2,390	2,650	3,280	30,100
	Ammonia (as N)	5	--	--	--	--	<0.04
	Ammonia plus organic nitrogen, unfiltered (as N)	1	0.16	--	--	--	--
	Ammonia, unfiltered (as N)	1	<0.01	--	--	--	--
	Dissolved organic carbon	2	1.5	--	--	--	2.2

Appendix E-2. Summary statistics for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; E, estimated value]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Spearfish aquifer —Continued	Nitrate (as N)	10	0.16	0.37	1.8	3.0	4.0
	Nitrate plus nitrite (as N)	2	2.3	--	--	--	9.8
	Nitrate+nitrite, unfiltered (as N)	1	0.90	--	--	--	--
	Nitrite (as N)	5	--	--	--	--	<0.008
	Organic nitrogen, unfiltered	5	--	--	--	--	<3.8
	Orthophosphate (as P)	5	E0.01	0.04	0.06	0.06	0.07
	Phosphorus, unfiltered	1	<0.01	--	--	--	--
	Total nitrogen, unfiltered	1	1.1	--	--	--	--
	Total nitrogen, unfiltered, analytically determined	4	0.43	1.4	2.6	3.4	3.8
	Aluminum	4	--	--	--	--	<100
	Antimony	4	--	--	--	--	<1.0
	Arsenic	4	1.1	1.7	2.2	3.6	4.7
	Barium	4	7.3	7.6	7.9	10.0	12.0
	Beryllium	4	--	--	--	--	<1.0
	Boron	12	100	380	435	800	2,000
	Cadmium	4	--	--	--	--	<0.2
	Chromium	4	--	--	--	--	<5.0
	Cobalt	4	--	--	--	--	<2.0
	Copper	4	<5.0	--	--	--	11.0
	Iron	5	<100	--	--	--	340
	Iron, unfiltered	10	--	18.9	60.4	184	1,900
	Lead	4	--	--	--	--	<1.0
	Manganese	4	<2.0	--	--	--	8.5
	Manganese, unfiltered	5	--	1.5	2.1	8.9	20.0
	Molybdenum	4	14.0	15.0	16.0	24.0	32.0
	Nickel	4	--	--	--	--	<4.0
	Selenium	4	3.0	14.5	31.5	103	169
	Strontium	4	7,200	7,800	9,150	9,950	10,000
	Vanadium	4	<10.0	--	--	--	19.0
	Zinc	4	<50.0	--	--	--	95.0

Appendix E-3

Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the NERB excluding Wind River structural basin, Wyoming

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Minnekahta aquifer	pH (standard units)	7	7.5	7.6	7.7	7.8	8.0
	Specific conductance (µS/cm)	7	400	904	1,860	2,190	2,380
	Hardness (as $CaCO_3$)	7	230	520	1,300	1,500	1,700
	Calcium	7	59.0	148	420	472	532
	Magnesium	7	21.0	37.0	51.0	78.0	83.0
	Potassium	7	1.3	1.6	1.9	2.6	2.6
	Sodium	7	3.2	3.4	3.8	5.4	5.5
	Sodium adsorption ratio (unitless)	7	0.04	0.04	0.10	0.10	0.10
	Alkalinity (as $CaCO_3$)	7	156	185	191	210	242
	Chloride	7	1.0	1.4	1.6	4.0	5.0
	Fluoride	7	0.20	0.20	0.30	0.40	0.40
	Silica	7	8.3	11.0	13.0	14.0	16.0
	Sulfate	7	24.0	261	1,000	1,260	1,420
	Total dissolved solids	7	245	648	1,620	1,970	2,200
	Ammonia plus organic nitrogen, unfiltered (as N)	1	0.21	--	--	--	--
	Ammonia, unfiltered (as N)	1	<0.01	--	--	--	--
	Nitrate (as N)	1	1.7	--	--	--	--
	Nitrate plus nitrite (as N)	5	0.34	0.38	1.4	3.2	4.7
	Nitrate+nitrite, unfiltered (as N)	1	4.6	--	--	--	--
	Organic nitrogen, unfiltered	1	0.21	--	--	--	--
	Orthophosphate (as P)	2	0.01	--	--	--	0.01
	Phosphorus	1	0.01	--	--	--	--
	Phosphorus, unfiltered	2	<0.01	--	--	--	0.02
	Total nitrogen, unfiltered	1	4.8	--	--	--	--
	Aluminum	2	--	--	--	--	<100
	Antimony	1	<1.0	--	--	--	--
	Arsenic	2	2.0	--	--	--	3.0
	Barium	1	<100	--	--	--	--
	Beryllium	2	<10.0	--	--	--	10.0
	Boron	7	50.0	50.0	50.0	110	210
	Cadmium	1	<2.0	--	--	--	--
	Chromium	2	--	--	--	--	<20.0
	Copper	2	<2.0	--	--	--	180
	Iron	2	--	--	--	--	<10.0
	Iron, unfiltered	3	<10.0	--	30.0	--	40.0
	Lead	2	<2.0	--	--	--	9.0
	Lithium	2	<10.0	--	--	--	20.0
	Manganese	2	--	--	--	--	<10.0
	Manganese, unfiltered	1	<10.0	--	--	--	--

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Minnekahta aquifer —Continued	Mercury	1	<0.5	--	--	--	--
	Molybdenum	2	2.0	--	--	--	6.0
	Nickel	1	2.0	--	--	--	--
	Selenium	2	<1.0	--	--	--	2.0
	Strontium	1	3,600	--	--	--	--
	Vanadium	2	2.0	--	--	--	3.4
	Zinc	2	50.0	--	--	--	200
Opeche confining unit	pH (standard units)	1	7.8	--	--	--	--
	Specific conductance (µS/cm)	1	855	--	--	--	--
	Hardness (as $CaCO_3$)	1	480	--	--	--	--
	Calcium	1	136	--	--	--	--
	Magnesium	1	35.0	--	--	--	--
	Potassium	1	2.0	--	--	--	--
	Sodium	1	4.9	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.10	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	243	--	--	--	--
	Chloride	1	2.2	--	--	--	--
	Fluoride	1	0.40	--	--	--	--
	Silica	1	17.0	--	--	--	--
	Sulfate	1	235	--	--	--	--
	Total dissolved solids	1	602	--	--	--	--
	Nitrate (as N)	1	0.68	--	--	--	--
	Boron	1	120	--	--	--	--
	Iron, unfiltered	1	30.0	--	--	--	--
Tensleep aquifer	pH (standard units)	18	7.2	7.7	8.0	8.1	8.4
	Specific conductance (µS/cm)	12	407	413	444	489	809
	Hardness (as $CaCO_3$)	13	210	220	250	270	410
	Calcium	19	35.0	43.0	52.0	210	370
	Magnesium	19	24.0	26.0	31.0	49.0	100
	Potassium	15	0.80	1.2	1.5	2.4	36.0
	Sodium	19	1.1	3.0	4.6	380	1,400
	Sodium adsorption ratio (unitless)	19	0.03	0.08	0.10	6.0	17.9
	Alkalinity (as $CaCO_3$)	19	100	192	225	258	560
	Chloride	19	0.20	1.3	6.0	550	1,400
	Fluoride	13	0.10	0.10	0.20	0.40	0.60
	Silica	13	7.8	8.9	9.8	11.0	14.0
	Sulfate	19	1.6	13.0	43.0	450	1,700

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Tensleep aquifer —Continued	Total dissolved solids	20	192	236	312	1,825	5,320
	Ammonia plus organic nitrogen, unfiltered (as N)	1	<0.1	--	--	--	--
	Nitrate (as N)	8	--	0.15	0.49	0.66	1.5
	Nitrate plus nitrite (as N)	2	0.90	--	--	--	1.6
	Phosphorus	1	<0.01	--	--	--	--
	Aluminum	1	30.0	--	--	--	--
	Arsenic	1	<1.0	--	--	--	--
	Barium	1	<100	--	--	--	--
	Boron	12	9.0	10.0	20.0	35.0	100
	Copper	1	<2.0	--	--	--	--
	Iron	1	<10.0	--	--	--	--
	Iron, unfiltered	12	20.0	25.0	40.0	50.0	140
	Lead	1	<2.0	--	--	--	--
	Lithium	1	<10.0	--	--	--	--
	Manganese	1	20.0	--	--	--	--
	Mercury	1	<0.5	--	--	--	--
	Molybdenum	1	1.0	--	--	--	--
	Selenium	1	1.0	--	--	--	--
	Strontium	1	550	--	--	--	--
	Vanadium	1	18.0	--	--	--	--
	Zinc	1	<20.0	--	--	--	--
Minnelusa aquifer	Dissolved oxygen	2	7.2	--	--	--	7.5
	pH (standard units)	31	6.5	7.4	7.7	7.9	8.5
	Specific conductance (µS/cm)	27	358	495	794	1,820	3,010
	Hardness (as $CaCO_3$)	33	39.0	260	435	1,000	2,200
	Calcium	33	11.0	76.0	118	240	615
	Magnesium	33	2.8	23.0	36.0	68.0	161
	Potassium	24	0.05	1.5	2.2	4.0	15.0
	Sodium	33	0.08	2.8	5.1	23.0	739
	Sodium adsorption ratio (unitless)	33	0.002	0.10	0.10	0.50	29.0
	Alkalinity (as $CaCO_3$)	33	77.0	182	230	253	652
	Chloride	33	0.10	1.4	4.0	11.0	760
	Fluoride	29	0.01	0.20	0.30	0.90	2.9
	Silica	27	2.3	8.5	10.0	11.0	14.0
	Sulfate	33	5.8	15.0	212	820	1,980
	Total dissolved solids	33	218	331	551	1,410	3,220
	Ammonia (as N)	2	--	--	--	--	<0.025

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Minnelusa aquifer —Continued	Ammonia plus organic nitrogen, unfiltered (as N)	3	0.03	--	0.03	--	0.16
	Ammonia, unfiltered (as N)	3	--	--	--	--	<0.01
	Nitrate (as N)	21	0.02	0.04	0.11	0.36	3.6
	Nitrate plus nitrite (as N)	2	0.03	--	--	--	0.13
	Nitrate+nitrite, unfiltered (as N)	3	0.20	--	0.20	--	0.72
	Nitrite (as N)	3	0.005	--	0.005	--	0.10
	Organic nitrogen, unfiltered	5	0.03	0.04	0.05	0.07	0.16
	Orthophosphate (as P)	2	0.03	--	--	--	0.04
	Phosphorus, unfiltered	3	--	--	--	--	<0.01
	Total nitrogen, unfiltered	3	0.23	--	0.23	--	0.88
	Total nitrogen, unfiltered, analytically determined	2	0.28	--	--	--	1.9
	Aluminum	5	--	--	--	--	<100
	Antimony	5	<0.5	--	--	--	1.0
	Arsenic	5	1.0	1.0	1.6	1.6	2.0
	Barium	2	60.0	--	--	--	330
	Beryllium	5	<1.0	--	--	--	20.0
	Boron	18	20.0	29.6	50.8	100	200
	Cadmium	2	--	--	--	--	<0.2
	Chromium	2	--	--	--	--	<5.0
	Cobalt	2	--	--	--	--	<2.0
	Copper	5	<2.0	--	--	--	6.0
	Iron	9	0.06	0.21	2.5	100	13,000
	Iron, unfiltered	24	20.0	28.6	96.0	490	14,000
	Lead	4	<0.5	--	--	--	2.0
	Lithium	3	--	--	--	--	<10.0
	Manganese	7	--	0.91	6.3	70.0	1,000
	Manganese, unfiltered	5	<2.0	--	--	--	16.0
	Mercury	3	--	--	--	--	<0.5
	Molybdenum	5	1.0	2.0	6.3	14.0	140
	Nickel	5	2.0	2.6	3.1	4.0	5.0
	Selenium	5	1.0	1.0	1.0	2.0	4.0
	Strontium	2	340	--	--	--	690
	Vanadium	5	1.6	2.8	3.6	4.7	6.6
	Zinc	5	<20.0	--	--	--	300
	Gross alpha radioactivity, in pCi/L	1	5.3	--	--	--	--
	Radium-226, in pCi/L	1	0.40	--	--	--	--
	Radium-228, in pCi/L	1	2.6	--	--	--	--
	Tritium, unfiltered, in pCi/L	3	<2.5	--	14.1	--	27.0

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Hartville aquifer (Hartville Uplift area)	pH (standard units)	2	8.0	--	--	--	8.4
	Specific conductance (µS/cm)	2	433	--	--	--	478
	Calcium	2	36.0	--	--	--	48.0
	Magnesium	2	17.0	--	--	--	18.0
	Potassium	2	6.0	--	--	--	9.0
	Sodium	2	25.0	--	--	--	27.0
	Sodium adsorption ratio (unitless)	2	0.79	--	--	--	0.92
	Alkalinity (as $CaCO_3$)	2	164	--	--	--	166
	Chloride	2	9.0	--	--	--	24.0
	Fluoride	2	0.60	--	--	--	2.3
	Silica	1	25.8	--	--	--	--
	Sulfate	2	43.0	--	--	--	44.0
	Total dissolved solids	2	256	--	--	--	305
	Nitrate plus nitrite (as N)	2	1.5	--	--	--	1.5
	Iron, unfiltered	2	430	--	--	--	2,550
	Manganese, unfiltered	1	31.0	--	--	--	--
	Gross alpha radioactivity, in pCi/L	2	11.3	--	--	--	15.5
	Radium-226, in pCi/L	2	0.14	--	--	--	0.63
	Radium-228, in pCi/L	2	0.51	--	--	--	0.68
	Uranium	1	10.9	--	--	--	--
Madison aquifer	Dissolved oxygen	2	2.0	--	--	--	3.8
	pH (standard units)	65	6.4	7.1	7.3	7.7	8.5
	Specific conductance (µS/cm)	57	99.0	480	707	925	4,280
	Hardness (as $CaCO_3$)	66	45.0	270	360	474	1,100
	Calcium	69	11.0	62.0	79.0	135	366
	Magnesium	69	4.1	27.0	32.0	41.0	104
	Potassium	66	0.20	1.3	2.0	5.2	69.0
	Sodium	69	0.60	2.2	3.7	32.0	760
	Sodium adsorption ratio (unitless)	69	0.02	0.08	0.10	0.71	11.0
	Alkalinity (as $CaCO_3$)	69	43.0	167	209	235	270
	Chloride	67	0.10	1.3	2.0	23.0	1,200
	Fluoride	65	0.10	0.30	0.50	2.0	5.5
	Silica	61	3.1	11.0	12.0	21.1	74.0
	Sulfate	69	1.0	28.0	148	270	1,130
	Total dissolved solids	69	65.0	281	454	668	3,490
	Ammonia (as N)	12	--	0.009	0.01	0.02	0.06
	Ammonia plus organic nitrogen (as N)	13	0.01	0.01	0.02	0.07	0.34

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Madison aquifer —Continued	Ammonia plus organic nitrogen, unfiltered (as N)	26	0.01	0.04	0.12	0.17	0.75
	Ammonia, unfiltered (as N)	15	--	0.005	0.01	0.01	0.07
	Dissolved organic carbon	3	0.40	--	0.60	--	5.1
	Nitrate (as N)	23	0.01	0.04	0.09	0.20	0.52
	Nitrate plus nitrite (as N)	23	0.10	0.16	0.19	0.26	1.1
	Nitrate, unfiltered (as N)	9	0.10	0.17	0.19	0.20	1.0
	Nitrate+nitrite, unfiltered (as N)	16	0.02	0.13	0.19	0.19	0.21
	Nitrite (as N)	14	--	--	--	--	<0.1
	Nitrite, unfiltered (as N)	9	--	--	--	--	<0.01
	Organic nitrogen	7	0.01	0.01	0.01	0.07	0.31
	Organic nitrogen, unfiltered	16	0.01	0.02	0.07	0.13	0.51
	Orthophosphate (as P)	10	0.01	0.01	0.01	0.01	0.02
	Phosphorus	20	--	0.007	0.009	0.01	0.02
	Phosphorus, unfiltered	16	--	0.009	0.01	0.01	0.02
	Total nitrogen	13	0.17	0.18	0.20	0.22	0.53
	Total nitrogen, unfiltered	18	0.06	0.18	0.24	0.30	0.73
	Aluminum	28	--	8.6	12.7	18.7	40.0
	Antimony	10	--	--	--	--	<10.0
	Arsenic	37	--	0.96	1.7	2.9	12.0
	Barium	31	--	--	--	--	<500
	Beryllium	20	--	--	--	--	<10.0
	Boron	56	2.0	8.9	28.0	88.3	890
	Cadmium	15	--	--	--	--	<10.0
	Chromium	16	<1.0	--	--	--	90.0
	Cobalt	2	--	--	--	--	<2.0
	Copper	30	--	0.49	1.9	7.4	180
	Iron	38	--	7.2	60.0	490	6,900
	Iron, unfiltered	14	40.0	70.0	215	420	580
	Lead	26	--	0.29	0.72	1.8	20.0
	Lithium	27	--	0.43	3.6	30.0	870
	Manganese	40	--	2.7	11.0	70.0	300
	Manganese, unfiltered	18	--	4.0	9.5	20.0	280
	Mercury	38	--	--	--	--	<1.0
	Molybdenum	29	1.0	2.1	4.2	8.3	50.0
	Nickel	11	1.0	1.4	1.9	2.6	3.0
	Selenium	36	--	0.72	1.4	2.8	11.0
	Strontium	27	70.0	250	520	3,000	6,000
	Vanadium	31	0.50	1.4	2.3	5.6	14.0
	Zinc	28	4.0	6.2	17.6	45.0	370

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Madison aquifer —Continued	Gross alpha radioactivity, in pCi/L	12	1.5	1.6	3.2	5.0	12.0
	Gross beta radioactivity, in pCi/L	23	--	1.0	3.4	12.0	93.0
	Radium-226, in pCi/L	14	0.10	0.19	0.90	1.4	8.3
	Radium-228, in pCi/L	13	0.10	0.22	0.52	1.4	8.7
	Radon-222, in pCi/L	2	168	--	--	--	190
	Tritium, unfiltered, in pCi/L	8	--	0.22	1.3	26.0	78.0
	Uranium	8	2.2	2.2	6.5	8.7	9.1
Whitewood aquifer	Hardness (as $CaCO_3$)	1	370	--	--	--	--
	Calcium	1	84.0	--	--	--	--
	Magnesium	1	39.0	--	--	--	--
	Potassium	1	2.4	--	--	--	--
	Sodium	1	4.7	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.10	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	180	--	--	--	--
	Chloride	1	2.8	--	--	--	--
	Fluoride	1	0.90	--	--	--	--
	Silica	1	22.0	--	--	--	--
	Sulfate	1	190	--	--	--	--
	Total dissolved solids	1	465	--	--	--	--
	Ammonia (as N)	1	0.03	--	--	--	--
	Ammonia plus organic nitrogen (as N)	1	0.21	--	--	--	--
	Ammonia plus organic nitrogen, unfiltered (as N)	1	0.16	--	--	--	--
	Dissolved organic carbon	1	0.20	--	--	--	--
	Nitrate plus nitrite (as N)	1	0.21	--	--	--	--
	Organic nitrogen	1	0.18	--	--	--	--
	Organic nitrogen, unfiltered	1	0.13	--	--	--	--
	Phosphorus	1	0.01	--	--	--	--
	Total nitrogen	1	0.42	--	--	--	--
	Total nitrogen, unfiltered	1	0.37	--	--	--	--
	Aluminum	1	<100	--	--	--	--
	Arsenic	1	<1.0	--	--	--	--
	Barium	1	200	--	--	--	--
	Boron	1	30.0	--	--	--	--
	Iron	1	1,900	--	--	--	--
	Lithium	1	9.0	--	--	--	--
	Manganese	1	170	--	--	--	--

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Whitewood aquifer—Continued	Mercury	1	<0.5	--	--	--	--
	Molybdenum	1	24.0	--	--	--	--
	Selenium	1	4.0	--	--	--	--
	Strontium	1	1,700	--	--	--	--
	Gross beta radioactivity, in pCi/L	1	4.4	--	--	--	--
Flathead aquifer	pH (standard units)	2	6.9	--	--	--	7.2
	Specific conductance (µS/cm)	2	160	--	--	--	1,320
	Hardness (as $CaCO_3$)	2	100	--	--	--	240
	Calcium	2	29.0	--	--	--	70.0
	Magnesium	2	7.0	--	--	--	15.0
	Potassium	2	1.7	--	--	--	23.0
	Sodium	2	2.4	--	--	--	180
	Sodium adsorption ratio (unitless)	2	0.10	--	--	--	5.1
	Alkalinity (as $CaCO_3$)	2	91.0	--	--	--	184
	Chloride	2	1.0	--	--	--	290
	Fluoride	2	0.20	--	--	--	4.5
	Silica	2	6.5	--	--	--	31.0
	Sulfate	2	9.4	--	--	--	74.0
	Total dissolved solids	2	112	--	--	--	793
	Ammonia plus organic nitrogen, unfiltered (as N)	2	0.16	--	--	--	1.1
	Ammonia, unfiltered (as N)	1	<0.01	--	--	--	--
	Nitrate+nitrite, unfiltered (as N)	1	0.62	--	--	--	--
	Organic nitrogen, unfiltered	1	0.16	--	--	--	--
	Phosphorus	1	<0.01	--	--	--	--
	Phosphorus, unfiltered	1	<0.01	--	--	--	--
	Total nitrogen, unfiltered	1	0.78	--	--	--	--
	Aluminum	2	--	--	--	--	<100
	Antimony	1	<1.0	--	--	--	--
	Arsenic	2	<1.0	--	--	--	7.0
	Barium	1	200	--	--	--	--
	Beryllium	1	<10.0	--	--	--	--
	Boron	2	<20.0	--	--	--	340
	Chromium	1	<20.0	--	--	--	--
	Copper	2	--	--	--	--	<2.0
	Iron	2	<10.0	--	--	--	80.0
	Iron, unfiltered	1	340	--	--	--	--
	Lithium	2	<10.0	--	--	--	400

Appendix E-3. Summary statistics for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Flathead aquifer —Continued	Manganese	2	20.0	--	--	--	50.0
	Manganese, unfiltered	1	20.0	--	--	--	--
	Mercury	2	--	--	--	--	<0.5
	Molybdenum	2	<1.0	--	--	--	1.0
	Nickel	1	6.0	--	--	--	--
	Selenium	2	<1.0	--	--	--	1.0
	Strontium	1	2,400	--	--	--	--
	Vanadium	2	0.60	--	--	--	1.5
	Zinc	2	<20.0	--	--	--	90.0
	Gross beta radioactivity, in pCi/L	1	19.0	--	--	--	--
	Radium-226, in pCi/L	1	14.0	--	--	--	--
Precambrian basal confining unit	pH (standard units)	1	7.0	--	--	--	--
	Specific conductance (µS/cm)	1	92.0	--	--	--	--
	Hardness (as $CaCO_3$)	1	34.0	--	--	--	--
	Calcium	1	9.6	--	--	--	--
	Magnesium	1	2.4	--	--	--	--
	Potassium	1	1.2	--	--	--	--
	Sodium	1	3.6	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.30	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	39.0	--	--	--	--
	Chloride	1	0.10	--	--	--	--
	Fluoride	1	0.10	--	--	--	--
	Silica	1	17.0	--	--	--	--
	Sulfate	1	5.3	--	--	--	--
	Total dissolved solids	1	63.0	--	--	--	--
	Nitrate (as N)	1	0.16	--	--	--	--
	Boron	1	10.0	--	--	--	--
	Iron, unfiltered	1	50.0	--	--	--	--

Appendix F

Summary statistics for environmental water samples from the Wind River structural basin within the NERB, Wyoming

Appendix F. Summary statistics for environmental water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; pCi/L, picocuries per liter; N, nitrogen;]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Cenozoic hydrogeologic units							
Fort Union aquifer	pH (standard units)	5	6.6	6.6	7.2	7.2	8.6
	Specific conductance (µS/cm)	2	1,200	--	--	--	2,210
	Hardness (as $CaCO_3$)	5	24.0	400	517	809	980
	Calcium	5	8.0	56.0	118	184	236
	Magnesium	5	1.0	39.0	54.0	85.0	95.0
	Potassium	3	1.0	--	10.0	--	15.0
	Sodium	5	5.0	12.0	37.0	175	317
	Sodium adsorption ratio (unitless)	5	0.10	0.30	0.60	2.4	28.1
	Alkalinity (as $CaCO_3$)	5	50.0	95.1	110	160	436
	Chloride	5	8.0	8.0	10.0	12.0	78.0
	Fluoride	2	0.90	--	--	--	5.8
	Silica	1	7.2	--	--	--	--
	Sulfate	4	255	323	545	960	1,220
	Total dissolved solids	5	400	641	767	1,120	1,940
	Boron	1	250	--	--	--	--
	Iron, unfiltered	4	2,700	11,100	25,750	45,000	58,000
	Gross beta radioactivity, in pCi/L	1	5.0	--	--	--	--
	Radium-226, in pCi/L	1	0.10	--	--	--	--
Mesozoic hydrogeologic units							
Mesaverde aquifer	pH (standard units)	1	8.6	--	--	--	--
	Specific conductance (µS/cm)	1	3,450	--	--	--	--
	Hardness (as $CaCO_3$)	1	83.0	--	--	--	--
	Calcium	1	20.0	--	--	--	--
	Magnesium	1	8.0	--	--	--	--
	Potassium	1	4.0	--	--	--	--
	Sodium	1	830	--	--	--	--
	Sodium adsorption ratio (unitless)	1	39.7	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	783	--	--	--	--
	Chloride	1	164	--	--	--	--
	Fluoride	1	0.86	--	--	--	--
	Sulfate	1	920	--	--	--	--
	Total dissolved solids	1	2,646	--	--	--	--
	Gross beta radioactivity, in pCi/L	1	10.0	--	--	--	--
	Radium-226, in pCi/L	1	0.10	--	--	--	--

Appendix F. Summary statistics for environmental water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; pCi/L, picocuries per liter; N, nitrogen;]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Mesozoic hydrogeologic units—Continued							
Muddy aquifer	pH (standard units)	1	8.4	--	--	--	--
	Calcium	1	10.0	--	--	--	--
	Magnesium	1	3.0	--	--	--	--
	Sodium	1	693	--	--	--	--
	Sodium adsorption ratio (unitless)	1	49.0	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	1,148	--	--	--	--
	Chloride	1	25.0	--	--	--	--
	Sulfate	1	56.0	--	--	--	--
	Total dissolved solids	1	1,690	--	--	--	--
Paleozoic hydrogeologic units							
Tensleep aquifer	pH (standard units)	1	7.6	--	--	--	--
	Specific conductance (µS/cm)	1	450	--	--	--	--
	Hardness (as $CaCO_3$)	1	210	--	--	--	--
	Calcium	1	55.0	--	--	--	--
	Magnesium	1	17.0	--	--	--	--
	Potassium	1	2.2	--	--	--	--
	Sodium	1	2.5	--	--	--	--
	Sodium adsorption ratio (unitless)	1	0.10	--	--	--	--
	Alkalinity (as $CaCO_3$)	1	136	--	--	--	--
	Chloride	1	4.0	--	--	--	--
	Fluoride	1	2.2	--	--	--	--
	Silica	1	9.4	--	--	--	--
	Sulfate	1	73.0	--	--	--	--
	Total dissolved solids	1	248	--	--	--	--
	Ammonia plus organic nitrogen, unfiltered (as N)	1	0.47	--	--	--	--
	Ammonia, unfiltered (as N)	1	<0.01	--	--	--	--
	Nitrate+nitrite, unfiltered (as N)	1	0.05	--	--	--	--
	Organic nitrogen, unfiltered	1	0.47	--	--	--	--
	Phosphorus, unfiltered	1	0.01	--	--	--	--
	Total nitrogen, unfiltered	1	0.52	--	--	--	--
	Aluminum	1	20.0	--	--	--	--
	Antimony	1	1.0	--	--	--	--
	Arsenic	1	5.0	--	--	--	--
	Beryllium	1	<10.0	--	--	--	--
	Boron	1	90.0	--	--	--	--
	Copper	1	<2.0	--	--	--	--
	Iron	1	550	--	--	--	--

Appendix F. Summary statistics for environmental water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; <, less than; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius; $CaCO_3$, calcium carbonate; pCi/L, picocuries per liter; N, nitrogen;]

Hydrogeologic unit	Characteristic and constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Paleozoic hydrogeologic units—Continued							
Tensleep aquifer —Continued	Iron, unfiltered	1	24,000	--	--	--	--
	Lead	1	2.0	--	--	--	--
	Lithium	1	<10.0	--	--	--	--
	Manganese	1	30.0	--	--	--	--
	Manganese, unfiltered	1	40.0	--	--	--	--
	Mercury	1	<0.5	--	--	--	--
	Molybdenum	1	1.0	--	--	--	--
	Nickel	1	4.0	--	--	--	--
	Selenium	1	2.0	--	--	--	--
	Vanadium	1	0.50	--	--	--	--

Appendix G-1

Summary statistics for produced-water samples from Cenozoic-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming

Appendix G-1. Summary statistics for produced-water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Wasatch aquifer (lower Tertiary aquifer system in Powder River structural basin)	pH (standard units)	21	6.1	6.7	6.8	7.3	7.8
	Calcium	21	155	254	378	515	578
	Magnesium	21	75.0	125	153	195	280
	Potassium	20	6.0	8.0	10.0	16.0	21.0
	Sodium	20	9.0	27.0	55.5	112	207
	Sodium adsorption ratio (unitless)	20	0.13	0.32	0.53	1.1	1.9
	Bicarbonate	21	317	451	476	549	634
	Chloride	21	4.0	10.0	13.0	20.0	51.0
	Sulfate	21	112	860	1,400	1,829	2,173
	Total dissolved solids	20	1,105	1,612	2,315	2,880	3,376
	Iron	1	--	--	--	--	2,000
Fort Union aquifer (lower Tertiary aquifer system in Powder River structural basin)	pH (standard units)	32	6.7	7.6	8.0	8.4	9.4
	Calcium	32	3.0	6.5	16.4	41.0	1,835
	Magnesium	31	1.0	2.0	8.0	21.0	205
	Potassium	22	0.99	3.0	7.5	20.0	170
	Sodium	34	10.0	256	377	925	63,210
	Sodium adsorption ratio (unitless)	32	0.10	13.0	28.7	45.6	379
	Bicarbonate	34	199	482	690	1,020	5,197
	Carbonate	11	2.0	10.0	24.0	48.1	301
	Chloride	32	1.0	9.5	37.5	435	101,000
	Sulfate	26	1.0	24.0	133	528	1,265
	Total dissolved solids	34	225	706	1,137	2,350	167,200
	Iron	11	150	420	2,500	8,100	190,000

Appendix G-2

Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the NERB excluding Wind River structural basin, Wyoming

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Lance aquifer (Upper Cretaceous aquifer system in the Powder River structural basin)	pH (standard units)	56	3.6	8.1	8.2	8.4	8.9
	Calcium	56	1.0	7.0	13.8	32.5	1,511
	Magnesium	46	1.0	2.9	5.0	24.0	446
	Potassium	27	2.0	10.0	13.0	16.0	43.0
	Sodium	57	387	664	1,164	1,480	16,780
	Sodium adsorption ratio (unitless)	56	8.7	35.4	60.1	105	403
	Bicarbonate	56	288	988	1,513	2,510	4,230
	Carbonate	25	24.0	36.0	60.0	96.0	512
	Chloride	57	46.0	210	430	676	25,000
	Sulfate	49	0.79	19.8	77.0	265	4,271
	Total dissolved solids	57	1,002	1,625	3,280	5,300	47,910
	Iron	16	50.0	150	1,040	4,920	72,000
Fox Hills aquifer (Upper Cretaceous aquifer system in the Powder River structural basin)	pH (standard units)	68	6.7	7.8	8.2	8.5	9.3
	Calcium	72	1.0	2.5	5.0	20.0	1,001
	Magnesium	57	0.40	1.0	2.0	7.0	563
	Potassium	58	--	3.0	5.5	11.0	168
	Sodium	78	125	338	419	669	1,408
	Sodium adsorption ratio (unitless)	74	2.9	30.8	47.8	71.7	122
	Bicarbonate	78	80.0	538	763	1,070	2,355
	Carbonate	34	6.6	19.0	36.0	60.0	252
	Chloride	78	7.0	25.0	56.0	210	3,003
	Fluoride	1	--	--	--	--	7.0
	Sulfate	73	2.5	81.0	167	276	2,600
	Total dissolved solids	78	325	920	1,234	1,998	6,758
	Iron	23	100	300	1,200	1,940	50,000
Lewis confining unit	pH (standard units)	2	8.2	--	--	--	8.6
	Calcium	3	4.0	--	29.0	--	31.0
	Magnesium	3	2.0	--	4.0	--	36.0
	Potassium	3	11.0	--	57.0	--	74.0
	Sodium	3	268	--	500	--	895
	Sodium adsorption ratio (unitless)	3	7.9	--	42.1	--	42.3
	Bicarbonate	3	451	--	634	--	1,098
	Carbonate	1	--	--	--	--	48.0
	Chloride	3	72.0	--	122	--	955
	Sulfate	3	120	--	245	--	250
	Total dissolved solids	3	1,027	--	1,252	--	2,519

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Pierre confining unit	pH (standard units)	28	7.1	7.9	8.3	8.5	8.8
	Calcium	38	1.0	7.0	18.0	36.0	304
	Magnesium	38	1.0	3.0	6.8	16.0	85.0
	Potassium	20	16.0	34.1	46.5	171	940
	Sodium	39	1,420	2,915	3,922	4,775	14,490
	Sodium adsorption ratio (unitless)	39	55.8	108	160	332	871
	Bicarbonate	38	740	1,842	2,190	2,548	5,417
	Carbonate	16	24.0	42.0	90.0	204	1,440
	Chloride	39	500	3,261	4,976	5,728	17,730
	Sulfate	35	0.99	2.0	7.0	120	1,248
	Total dissolved solids	39	3,399	7,825	10,480	12,450	37,370
	Iron	3	60.0	--	990	--	1,550
Mesaverde aquifer	pH (standard units)	391	5.1	7.5	7.9	8.2	9.4
	Calcium	466	1.5	27.0	56.0	99.0	4,316
	Magnesium	447	1.0	8.0	13.0	22.0	899
	Potassium	300	2.1	29.0	46.0	92.0	6,000
	Sodium	466	69.0	4,102	5,266	6,174	17,010
	Sodium adsorption ratio (unitless)	466	2.4	98.1	154	198	497
	Bicarbonate	462	117	1,244	1,688	2,120	3,927
	Carbonate	96	1.2	48.0	72.0	108	606
	Chloride	466	6.0	5,000	7,375	8,800	29,010
	Fluoride	3	5.3	--	5.6	--	5.7
	Sulfate	341	1.0	8.0	30.0	194	4,967
	Total dissolved solids	463	399	10,480	14,170	16,280	48,670
	Boron	7	4,030	8,800	12,400	13,130	17,190
	Iron	155	51.0	2,300	6,900	15,100	848,000
Cody confining unit	pH (standard units)	380	4.6	7.5	8.0	8.2	9.4
	Calcium	413	1.0	13.0	35.0	149	1,678
	Magnesium	394	1.0	5.0	11.0	35.5	564
	Potassium	344	2.0	23.0	48.0	197	28,590
	Sodium	413	344	3,017	5,250	9,100	25,270
	Sodium adsorption ratio (unitless)	414	3.0	132	181	264	596
	Bicarbonate	409	8.0	736	1,476	1,880	8,800
	Carbonate	74	8.0	48.0	84.0	204	1,262
	Chloride	415	8.0	3,347	7,340	14,000	39,130
	Sulfate	290	0.99	9.0	17.5	59.0	5,879

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Cody confining unit —Continued	Total dissolved solids	415	97.2	7,854	13,400	23,900	76,100
	Boron	2	2,020	--	--	--	10,070
	Iron	103	430	10,160	31,550	80,930	856,000
Steele confining unit	pH (standard units)	33	7.7	8.0	8.3	8.4	8.9
	Calcium	33	2.0	17.0	23.0	42.0	95.0
	Magnesium	31	1.0	4.0	7.0	12.1	27.0
	Potassium	1	--	--	--	--	20.0
	Sodium	33	568	2,720	3,216	3,949	4,320
	Sodium adsorption ratio (unitless)	33	42.8	108	135	156	585
	Bicarbonate	33	683	1,159	2,000	2,165	2,490
	Carbonate	19	24.0	59.0	84.0	144	192
	Chloride	33	156	3,100	3,740	5,400	6,100
	Sulfate	26	5.0	15.0	22.0	30.0	676
	Total dissolved solids	33	1,989	6,832	8,087	10,070	10,960
Niobrara confining unit	pH (standard units)	8	5.9	6.5	7.5	8.2	8.5
	Calcium	32	12.0	254	557	828	4,565
	Magnesium	32	10.0	25.0	65.5	99.0	201
	Potassium	28	16.0	85.0	129	240	376
	Sodium	32	678	3,979	9,005	10,900	16,540
	Sodium adsorption ratio (unitless)	32	17.5	59.6	87.7	109	249
	Bicarbonate	32	254	541	867	1,135	5,490
	Carbonate	5	0.00	24.0	84.0	240	240
	Chloride	32	240	5,983	14,850	19,760	29,420
	Sulfate	29	11.0	21.0	29.0	50.0	2,202
	Total dissolved solids	32	1,984	12,150	25,220	32,230	47,800
	Iron	4	1,870	1,870	6,935	72,300	132,600
Carlile confining unit	pH (standard units)	16	6.5	6.9	7.3	8.0	9.1
	Calcium	69	3.0	472	642	929	5,693
	Magnesium	68	0.99	66.0	94.5	117	484
	Potassium	69	4.0	161	913	1,376	2,854
	Sodium	70	530	11,340	13,700	16,500	30,460
	Sodium adsorption ratio (unitless)	70	37.5	125	140	151	671
	Bicarbonate	70	307	476	549	649	2,745
	Carbonate	4	5.0	20.5	180	414	504
	Chloride	70	63.0	20,860	23,916	28,300	50,970

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Carlile confining unit —Continued	Fluoride	1	--	--	--	--	4.6
	Sulfate	63	3.0	12.0	24.0	41.0	1,321
	Total dissolved solids	70	86.2	34,970	40,350	47,300	84,100
	Boron	1	--	--	--	--	11,400
	Iron	9	130	2,000	38,780	81,900	1,088,000
Frontier aquifer	pH (standard units)	265	4.4	7.9	8.2	8.4	11.8
	Specific conductance (uS/cm)	1	--	--	--	--	3,530
	Calcium	315	1.0	14.0	27.2	73.0	13,540
	Magnesium	301	1.0	4.0	9.0	22.3	4,275
	Potassium	196	1.0	11.0	20.5	51.0	33,300
	Sodium	318	61.0	1,467	2,534	4,526	39,630
	Sodium adsorption ratio (unitless)	316	1.3	63.5	105	169	345
	Alkalinity (as CaCO3)	1	--	--	--	--	1,820
	Bicarbonate	317	12.0	855	1,610	2,754	6,921
	Carbonate	149	12.0	60.0	132	243	1,443
	Chloride	321	8.0	775	2,020	5,150	98,000
	Fluoride	1	--	--	--	--	13.0
	Sulfate	284	1.0	31.0	153	550	10,520
	Total dissolved solids	320	227	3,848	7,019	11,840	156,600
	Boron	3	1,800	--	10,090	--	11,120
	Iron	12	200	1,295	12,270	31,900	54,000
Greenhorn confining unit	Calcium	2	53.0	--	--	--	62.0
	Magnesium	2	41.0	--	--	--	54.0
	Sodium	2	7,021	--	--	--	7,902
	Sodium adsorption ratio (unitless)	2	162	--	--	--	191
	Bicarbonate	2	420	--	--	--	560
	Chloride	2	10,740	--	--	--	12,050
	Sulfate	2	53.0	--	--	--	134
	Total dissolved solids	2	18,420	--	--	--	20,670
Mowry confining unit	pH (standard units)	5	7.2	7.2	7.5	7.6	8.5
	Calcium	9	4.0	80.0	271	698	2,590
	Magnesium	9	1.0	43.0	69.0	110	336
	Potassium	6	5.0	48.0	59.0	76.0	368
	Sodium	9	678	4,144	9,650	12,200	13,900

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Mowry confining unit —Continued	Sodium adsorption ratio (unitless)	9	55.7	78.6	94.6	142	220
	Bicarbonate	9	337	658	1,110	1,601	2,165
	Carbonate	1	--	--	--	--	86.0
	Chloride	9	20.0	2,500	17,200	20,300	23,400
	Fluoride	2	0.90	--	--	--	13.5
	Sulfate	9	3.0	14.0	28.0	51.0	7,942
	Total dissolved solids	9	1,608	13,440	27,500	35,200	38,600
	Boron	2	9,600	--	--	--	9,800
	Selenium	1	--	--	--	--	240
Muddy aquifer	pH (standard units)	277	3.6	7.5	7.9	8.2	9.8
	Calcium	293	1.2	22.1	45.0	98.0	2,294
	Magnesium	290	0.20	7.0	16.0	31.0	990
	Potassium	236	1.3	18.1	37.1	57.0	8,100
	Sodium	300	2.0	2,292	4,777	7,343	23,050
	Sodium adsorption ratio (unitless)	295	0.28	93.4	152	199	499
	Bicarbonate	299	7.3	1,074	1,730	2,208	5,520
	Carbonate	85	0.00	36.0	48.0	96.0	2,244
	Chloride	301	2.0	2,620	6,294	10,350	38,500
	Fluoride	9	0.40	0.60	1.9	5.2	8.8
	Sulfate	257	0.80	11.0	35.0	99.0	6,000
	Total dissolved solids	300	37.0	5,867	12,630	18,870	64,780
	Boron	16	900	6,400	10,150	12,250	19,000
	Iron	21	600	6,890	17,000	29,000	278,000
	Selenium	9	30.0	80.0	90.0	130	300
Newcastle aquifer	pH (standard units)	151	6.1	7.7	8.0	8.3	9.8
	Calcium	160	2.0	23.5	42.5	76.5	910
	Magnesium	156	1.0	10.5	20.0	35.5	176
	Potassium	72	2.0	14.0	22.0	46.0	14,540
	Sodium	163	141	1,624	3,650	4,803	11,370
	Sodium adsorption ratio (unitless)	161	5.5	57.8	102	154	587
	Bicarbonate	163	177	904	1,720	2,823	9,050
	Carbonate	65	--	54.0	119	300	1,930
	Chloride	163	6.0	1,040	3,749	6,300	18,570
	Sulfate	145	1.0	15.0	50.0	337	6,700
	Total dissolved solids	163	707	4,357	9,531	12,400	31,500
	Boron	3	2,200	--	5,100	--	13,700

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Newcastle aquifer —Continued	Iron	5	740	950	3,600	6,300	64,550
	Selenium	1	--	--	--	--	40.0
Skull Creek confining unit	pH (standard units)	2	8.5	--	--	--	9.8
	Calcium	2	24.2	--	--	--	368
	Magnesium	1	--	--	--	--	24.2
	Potassium	1	--	--	--	--	68.0
	Sodium	2	4,341	--	--	--	4,643
	Sodium adsorption ratio (unitless)	2	66.7	--	--	--	149
	Bicarbonate	2	695	--	--	--	2,228
	Carbonate	2	66.5	--	--	--	264
	Chloride	2	5,433	--	--	--	7,100
	Sulfate	2	2.0	--	--	--	81.0
	Total dissolved solids	2	12,120	--	--	--	12,870
Cloverly aquifer	pH (standard units)	93	5.4	7.7	8.0	8.3	9.3
	Calcium	110	3.0	20.0	52.5	109	1,216
	Magnesium	98	1.0	8.0	15.0	29.0	401
	Potassium	50	4.0	14.0	24.5	45.0	18,180
	Sodium	107	573	1,681	4,093	6,641	18,420
	Sodium adsorption ratio (unitless)	110	10.3	78.0	131	165	362
	Bicarbonate	110	224	975	1,321	1,574	6,564
	Carbonate	35	12.0	36.0	72.0	134	1,104
	Chloride	110	40.0	1,710	5,300	9,300	28,940
	Sulfate	101	8.0	248	615	1,036	3,280
	Total dissolved solids	110	1,484	5,037	11,120	17,920	50,760
	Boron	1	--	--	--	--	19,270
	Iron	1	--	--	--	--	170
Inyan Kara aquifer	pH (standard units)	293	5.7	7.9	8.2	8.6	10.7
	Calcium	296	0.11	7.5	13.0	29.5	1,623
	Magnesium	273	1.0	2.0	4.0	9.0	158
	Potassium	147	1.0	5.0	9.0	16.0	360
	Sodium	304	12.0	660	947	1,884	24,140
	Sodium adsorption ratio (unitless)	299	0.86	46.8	67.3	101	306
	Bicarbonate	305	61.0	732	1,208	1,756	5,671
	Carbonate	157	4.0	52.0	96.0	168	1,022
	Chloride	306	4.0	76.0	271	1,140	36,000

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Inyan Kara aquifer —Continued	Fluoride	1	--	--	--	--	2.7
	Sulfate	294	1.0	160	390	802	7,500
	Total dissolved solids	305	188	1,780	2,615	4,947	67,260
	Boron	5	900	1,300	1,600	9,030	30,600
	Iron	30	100	2,000	8,895	17,780	59,150
	Selenium	1	--	--	--	--	130
Morrison confining unit	pH (standard units)	15	6.9	7.6	7.9	8.2	8.6
	Calcium	19	7.0	40.0	251	348	629
	Magnesium	17	1.0	19.0	43.0	53.0	104
	Potassium	4	26.0	45.0	71.5	585	1,090
	Sodium	20	14.0	1,947	3,123	3,862	18,440
	Sodium adsorption ratio (unitless)	19	0.16	37.2	56.9	137	187
	Bicarbonate	19	85.0	370	450	1,171	2,600
	Carbonate	7	22.0	37.0	72.0	96.0	168
	Chloride	20	44.1	249	352	3,713	27,600
	Sulfate	19	20.0	1,182	3,856	6,568	8,200
	Total dissolved solids	20	1,952	6,283	10,230	12,580	51,760
	Iron	2	1,980	--	--	--	3,050
Sundance aquifer	pH (standard units)	82	4.9	7.5	8.0	8.3	9.9
	Calcium	107	8.0	70.0	141	264	2,667
	Magnesium	104	4.0	18.5	33.0	56.1	945
	Potassium	35	6.0	11.0	25.0	49.0	160
	Sodium	107	199	1,848	2,909	3,697	12,210
	Sodium adsorption ratio (unitless)	107	2.3	38.4	54.8	74.9	159
	Bicarbonate	107	68.0	495	701	983	2,452
	Carbonate	25	5.0	36.0	60.0	97.0	300
	Chloride	107	16.0	430	1,790	3,440	17,330
	Sulfate	106	2.0	1,832	2,902	3,958	8,562
	Total dissolved solids	106	1,233	5,804	8,560	11,240	33,660
	Iron	3	90.0	--	240	--	18,410
Chugwater confining unit	pH (standard units)	32	5.3	7.7	8.3	8.5	9.4
	Calcium	32	3.0	15.5	21.0	46.0	532
	Magnesium	32	1.0	5.0	12.0	21.5	218
	Potassium	20	3.0	4.5	5.5	10.0	38.0
	Sodium	32	367	488	708	897	10,500

Appendix G-2. Summary statistics for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter. --, not applicable; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Chugwater confining unit —Continued	Sodium adsorption ratio (unitless)	32	7.4	24.0	28.2	38.6	121
	Bicarbonate	32	110	604	1,049	1,745	3,660
	Carbonate	17	12.0	36.0	78.0	108	300
	Chloride	31	32.0	56.0	112	248	14,100
	Sulfate	31	40.0	230	380	635	4,880
	Total dissolved solids	32	1,049	1,544	2,174	3,465	30,500
	Iron	1	--	--	--	--	920
Spearfish aquifer	pH (standard units)	1	--	--	--	--	7.7
	Calcium	1	--	--	--	--	500
	Magnesium	1	--	--	--	--	117
	Potassium	1	--	--	--	--	124
	Sodium	1	--	--	--	--	3,759
	Sodium adsorption ratio (unitless)	1	--	--	--	--	39.3
	Bicarbonate	1	--	--	--	--	827
	Chloride	1	--	--	--	--	3,940
	Sulfate	1	--	--	--	--	3,950
	Total dissolved solids	1	--	--	--	--	10,320
Goose Egg confining unit	pH (standard units)	7	7.8	8.1	8.2	8.2	8.5
	Calcium	7	251	306	322	474	474
	Magnesium	7	24.0	41.0	52.0	65.0	97.0
	Potassium	2	30.0	--	--	--	50.0
	Sodium	7	334	429	1,276	2,981	3,243
	Sodium adsorption ratio (unitless)	7	3.9	6.6	16.6	38.0	43.1
	Bicarbonate	7	78.0	108	537	1,150	1,340
	Carbonate	2	10.0	--	--	--	14.0
	Chloride	7	160	228	680	700	812
	Sulfate	7	282	1,716	2,565	5,522	5,806
	Total dissolved solids	7	2,028	2,802	5,186	10,150	10,800

Appendix G-3

Summary statistics for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the NERB excluding Wind River structural basin, Wyoming

Appendix G-3. Summary statistics for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Minnekahta aquifer	pH (standard units)	12	6.1	7.1	7.5	7.9	9.0
	Calcium	13	294	522	589	1,708	27,730
	Magnesium	12	34.0	110	172	327	10,020
	Potassium	5	13.0	26.0	42.0	48.0	450
	Sodium	13	132	407	2,284	30,810	72,650
	Sodium adsorption ratio (unitless)	13	1.2	4.8	28.8	132	348
	Bicarbonate	13	83.0	207	256	390	695
	Carbonate	2	36.0	--	--	--	120
	Chloride	13	21.0	46.1	420	50,000	125,000
	Sulfate	13	688	2,483	3,850	4,650	5,954
	Total dissolved solids	13	2,910	4,066	8,678	88,730	195,900
	Iron	1	--	--	--	--	40,000
Tensleep aquifer	pH (standard units)	156	6.2	7.1	7.6	8.0	11.4
	Calcium	173	6.0	219	299	403	2,205
	Magnesium	172	2.0	37.0	54.0	79.0	439
	Potassium	61	3.0	38.0	90.0	142	990
	Sodium	168	61.7	429	562	1,111	13,850
	Sodium adsorption ratio (unitless)	173	0.36	5.9	8.1	14.2	174
	Bicarbonate	171	73.0	171	244	407	2,795
	Carbonate	22	6.0	24.0	36.5	79.0	1,780
	Chloride	173	8.0	310	600	845	18,500
	Sulfate	173	7.0	821	1,080	1,576	10,320
	Total dissolved solids	173	1,138	2,349	2,962	4,553	41,000
	Iron	8	100	185	625	4,400	56,000
Amsden hydrogeologic unit	pH (standard units)	4	6.4	6.8	7.2	8.4	9.6
	Calcium	7	23.0	80.0	292	332	415
	Magnesium	6	8.0	12.0	41.0	63.0	114
	Potassium	1	--	--	--	--	175
	Sodium	7	468	474	548	868	1,223
	Sodium adsorption ratio (unitless)	7	6.6	7.0	8.3	14.3	56.0
	Bicarbonate	6	8.0	123	279	425	925
	Carbonate	3	14.0	--	34.0	--	483
	Chloride	7	12.0	420	612	742	940
	Sulfate	7	484	573	1,025	1,154	1,597
	Total dissolved solids	7	1,964	2,069	2,538	3,186	3,921
Minnelusa aquifer	pH (standard units)	861	3.9	6.8	7.3	7.8	10.8
	Calcium	929	1.0	432	607	976	16,000
	Magnesium	916	1.0	81.5	139	320	9,200

Appendix G-3. Summary statistics for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Minnelusa aquifer —Continued	Potassium	548	2.0	89.0	217	806	21,240
	Sodium	928	2.0	825	4,675	22,200	115,100
	Sodium adsorption ratio (unitless)	929	0.02	10.3	46.0	168	1,159
	Bicarbonate	903	2.1	268	458	708	13,680
	Carbonate	69	2.4	36.0	60.0	120	4,805
	Chloride	927	3.0	520	5,736	36,000	185,800
	Fluoride	2	0.20	--	--	--	2.0
	Sulfate	927	4.0	1,730	2,728	4,100	150,000
	Total dissolved solids	928	91.9	4,438	15,250	64,620	307,700
	Boron	11	1,200	4,800	17,500	45,600	101,940
	Iron	131	40.0	500	2,000	19,000	1,500,000
	Selenium	7	20.0	120	200	800	1,300
Madison aquifer	pH (standard units)	48	4.3	7.0	7.5	7.8	9.6
	Specific conductance (uS/cm)	1	--	--	--	--	550
	Calcium	54	2.0	156	275	334	1,746
	Magnesium	53	1.0	31.0	51.0	61.0	392
	Potassium	22	2.0	9.0	25.0	45.0	196
	Sodium	54	3.0	315	468	702	18,290
	Sodium adsorption ratio (unitless)	54	0.07	4.2	6.4	11.6	223
	Bicarbonate	53	12.0	131	178	299	1,269
	Carbonate	6	7.0	12.0	19.5	24.0	227
	Chloride	54	2.0	86.0	555	693	29,600
	Fluoride	2	1.4	--	--	--	3.0
	Sulfate	54	25.0	707	996	1,142	3,864
	Total dissolved solids	53	282	1,900	2,550	3,070	53,900
	Boron	2	40.0	--	--	--	360
	Iron	8	400	935	1,100	35,950	90,000
	Selenium	2	1.0	--	--	--	1.0
Bighorn aquifer	pH (standard units)	5	7.1	7.4	7.5	7.8	10.8
	Calcium	5	210	254	351	500	735
	Magnesium	4	15.0	41.0	71.0	99.5	124
	Sodium	4	132	358	671	1,036	1,313
	Sodium adsorption ratio (unitless)	5	2.2	6.8	7.4	14.6	53.8
	Bicarbonate	5	120	270	360	370	410
	Carbonate	1	--	--	--	--	426
	Chloride	5	18.0	110	140	180	200
	Sulfate	5	826	1,876	3,326	3,675	5,308
	Total dissolved solids	5	1,304	3,219	5,286	5,917	9,061

Appendix G-3. Summary statistics for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area excluding Wind River structural basin, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius; $CaCO_3$, calcium carbonate]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Gallatin hydrogeologic unit	Calcium	2	318	--	--	--	332
	Sodium	2	550	--	--	--	609
	Sodium adsorption ratio (unitless)	2	8.5	--	--	--	9.2
	Bicarbonate	1	--	--	--	--	43.0
	Chloride	2	760	--	--	--	825
	Sulfate	2	881	--	--	--	918
	Total dissolved solids	2	2,509	--	--	--	2,705
Precambrian basal confining unit	pH (standard units)	1	--	--	--	--	9.6
	Calcium	1	--	--	--	--	36.0
	Magnesium	1	--	--	--	--	4.9
	Potassium	1	--	--	--	--	19.0
	Sodium	1	--	--	--	--	1,197
	Sodium adsorption ratio (unitless)	1	--	--	--	--	49.7
	Bicarbonate	1	--	--	--	--	248
	Carbonate	1	--	--	--	--	37.5
	Chloride	1	--	--	--	--	568
	Sulfate	1	--	--	--	--	1,608
	Total dissolved solids	1	--	--	--	--	3,718

Appendix H

Summary statistics for produced-water samples from hydrogeologic units in the Wind River structural basin within the NERB, Wyoming

Appendix H. Summary statistics for produced-water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Wind River aquifer	pH (standard units)	4	7.2	7.8	8.5	8.6	8.6
	Calcium	4	11.0	11.5	14.5	19.5	22.0
	Magnesium	4	2.0	2.5	4.0	7.0	9.0
	Potassium	3	9.0	--	12.0	--	20.0
	Sodium	4	440	507	614	834	1,013
	Sodium adsorption ratio (unitless)	4	31.0	32.9	35.4	42.7	49.4
	Bicarbonate	4	708	714	751	1,074	1,366
	Carbonate	3	72.0	--	96.0	--	132
	Chloride	4	136	185	267	520	740
	Sulfate	4	60.0	99.0	178	259	300
	Total dissolved solids	4	1,117	1,301	1,638	2,197	2,603
Fort Union aquifer	pH (standard units)	31	6.4	7.6	7.9	8.4	8.9
	Calcium	31	3.0	9.0	16.0	24.0	1,242
	Magnesium	28	0.70	3.0	5.0	7.0	152
	Potassium	23	5.3	15.0	33.0	132	3,560
	Sodium	31	49.9	1,024	1,327	2,290	4,920
	Sodium adsorption ratio (unitless)	31	4.7	55.9	75.5	142	221
	Bicarbonate	31	114	1,513	2,294	3,001	3,855
	Carbonate	10	24.0	32.0	120	216	408
	Chloride	31	56.0	486	900	1,994	6,087
	Sulfate	29	3.0	20.0	70.0	257	1,249
	Total dissolved solids	31	270	2,459	3,720	6,087	15,900
	Iron	6	490	3,540	11,580	51,600	643,000
Lance aquifer	pH (standard units)	33	6.8	8.0	8.3	8.5	9.2
	Calcium	33	3.7	12.0	23.0	56.0	627
	Magnesium	31	1.0	3.7	10.0	21.0	111
	Potassium	19	9.3	18.2	72.0	126	425
	Sodium	33	803	1,440	2,055	2,870	7,197
	Sodium adsorption ratio (unitless)	33	38.0	70.3	90.2	113	289
	Bicarbonate	33	708	1,952	2,700	3,387	5,490
	Carbonate	13	34.0	60.9	70.0	128	252
	Chloride	33	90.0	504	1,090	2,260	10,000
	Sulfate	30	1.0	14.8	133	559	5,119
	Total dissolved solids	33	2,236	3,830	5,750	8,670	21,520
	Iron	14	50.0	82.0	337	810	21,000

Appendix H. Summary statistics for produced-water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Meeteetse confining unit	pH (standard units)	1	--	--	--	--	8.3
	Calcium	1	--	--	--	--	121
	Magnesium	1	--	--	--	--	48.0
	Potassium	1	--	--	--	--	23.0
	Sodium	1	--	--	--	--	970
	Sodium adsorption ratio (unitless)	1	--	--	--	--	18.9
	Bicarbonate	1	--	--	--	--	1,964
	Carbonate	1	--	--	--	--	84.0
	Chloride	1	--	--	--	--	422
	Sulfate	1	--	--	--	--	350
	Total dissolved solids	1	--	--	--	--	3,983
Mesaverde aquifer	pH (standard units)	1	--	--	--	--	9.5
	Calcium	1	--	--	--	--	11.0
	Magnesium	2	3.0	--	--	--	7.0
	Sodium	1	--	--	--	--	538
	Sodium adsorption ratio (unitless)	2	23.7	--	--	--	66.6
	Bicarbonate	2	224	--	--	--	1,304
	Carbonate	1	--	--	--	--	165
	Chloride	2	27.0	--	--	--	81.0
	Sulfate	1	--	--	--	--	431
	Total dissolved solids	2	1,132	--	--	--	1,263
Cody confining unit	Calcium	2	37.0	--	--	--	253
	Magnesium	2	218	--	--	--	325
	Sodium	2	467	--	--	--	1,666
	Sodium adsorption ratio (unitless)	2	4.6	--	--	--	23.0
	Bicarbonate	2	905	--	--	--	1,600
	Carbonate	1	--	--	--	--	79.0
	Chloride	2	42.0	--	--	--	302
	Sulfate	2	2,093	--	--	--	2,626
	Total dissolved solids	2	3,625	--	--	--	5,715
Frontier aquifer	pH (standard units)	3	6.4	--	8.2	--	8.6
	Calcium	11	6.0	14.0	30.0	76.0	268
	Magnesium	10	1.0	8.0	14.0	18.0	31.0
	Potassium	1	--	--	--	--	122
	Sodium	10	1,149	1,562	4,421	5,910	8,567

Appendix H. Summary statistics for produced-water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter]

Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Frontier aquifer —Continued	Sodium adsorption ratio (unitless)	11	22.6	48.4	136	198	229
	Bicarbonate	11	251	1,700	2,174	2,754	4,730
	Carbonate	5	73.0	119	180	240	378
	Chloride	11	44.0	940	4,340	8,024	11,700
	Sulfate	7	10.0	13.0	40.0	96.0	761
	Total dissolved solids	11	1,161	3,808	9,734	16,310	22,700
	Iron	1	--	--	--	--	57,400
Mowry confining unit	Calcium	1	--	--	--	--	11.0
	Magnesium	1	--	--	--	--	2.0
	Sodium adsorption ratio (unitless)	1	--	--	--	--	30.7
	Bicarbonate	1	--	--	--	--	809
	Carbonate	1	--	--	--	--	35.0
	Chloride	1	--	--	--	--	26.0
	Sulfate	1	--	--	--	--	186
	Total dissolved solids	1	--	--	--	--	1,490
Muddy aquifer	pH (standard units)	14	6.8	8.1	8.3	8.5	9.3
	Calcium	14	8.0	14.0	25.5	135	800
	Magnesium	13	3.0	4.0	10.0	14.1	240
	Potassium	5	19.0	20.0	37.0	50.0	204
	Sodium	14	705	1,202	2,412	4,338	16,170
	Sodium adsorption ratio (unitless)	14	36.6	65.9	95.1	139	187
	Bicarbonate	14	363	1,220	2,056	2,489	4,510
	Carbonate	10	36.0	84.0	186	228	243
	Chloride	14	21.0	450	2,928	5,800	26,150
	Sulfate	12	20.0	22.5	58.0	152	588
	Total dissolved solids	14	1,688	3,029	6,783	12,170	43,790
	Iron	1	--	--	--	--	154,000
Cloverly aquifer	pH (standard units)	7	7.0	7.5	8.2	8.5	8.5
	Calcium	7	8.0	9.0	277	290	818
	Magnesium	7	2.0	3.0	64.0	107	222
	Sodium	7	902	993	1,778	3,041	16,320
	Sodium adsorption ratio (unitless)	7	19.6	24.6	43.1	81.4	131
	Bicarbonate	7	561	604	663	1,818	1,830
	Carbonate	3	24.1	--	144	--	156
	Chloride	7	128	132	402	3,528	26,830
	Sulfate	7	67.0	152	1,842	3,606	3,606
	Total dissolved solids	7	2,158	2,429	6,460	9,151	44,620

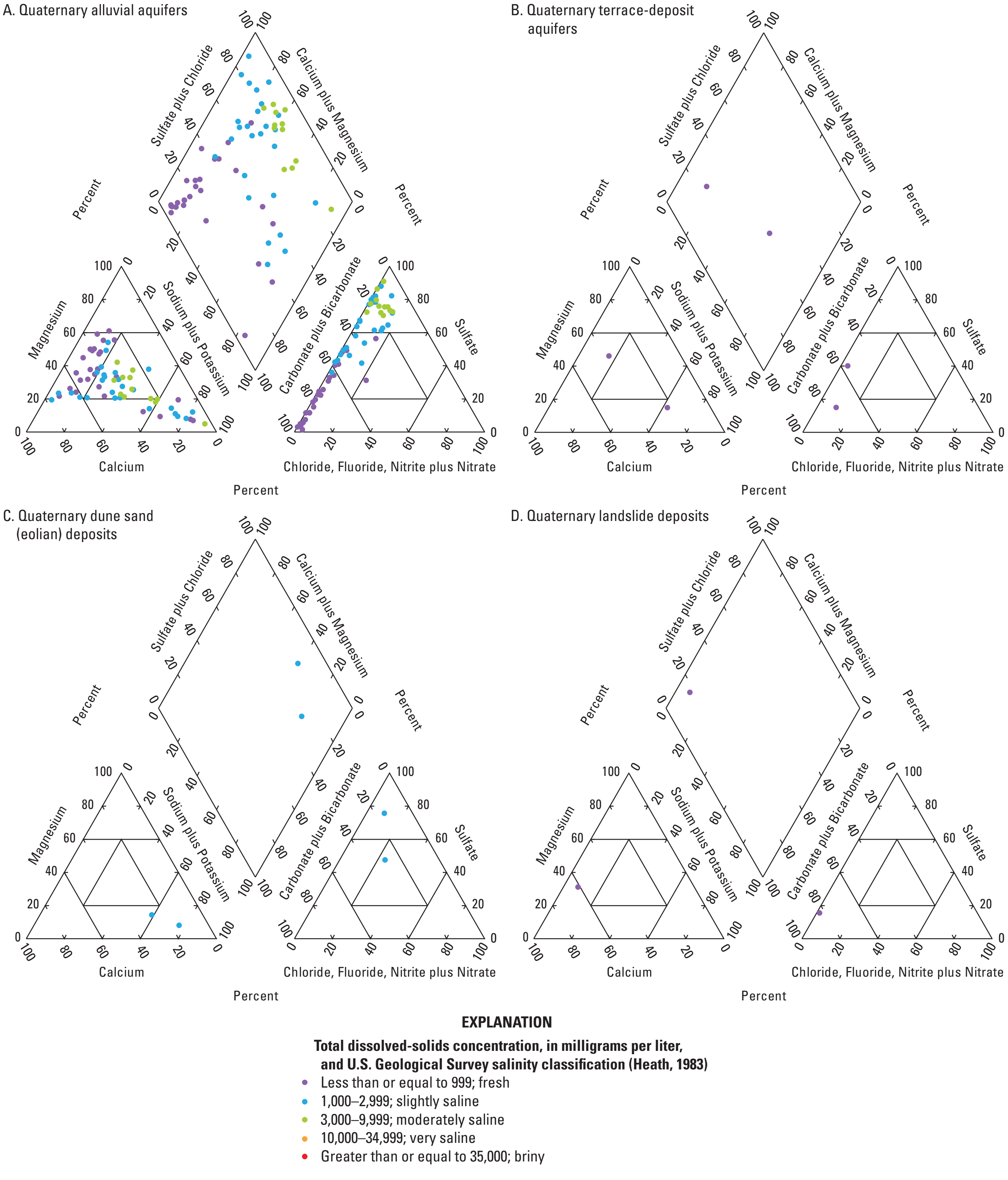
Appendix H. Summary statistics for produced-water samples from Cenozoic-, Mesozoic-, and Paleozoic-age hydrogeologic units in the Wind River structural basin, Northeastern River Basins study area, Wyoming.—Continued

[Values in black are in milligrams per liter unless otherwise noted; --, not applicable; values in blue are in micrograms per liter]

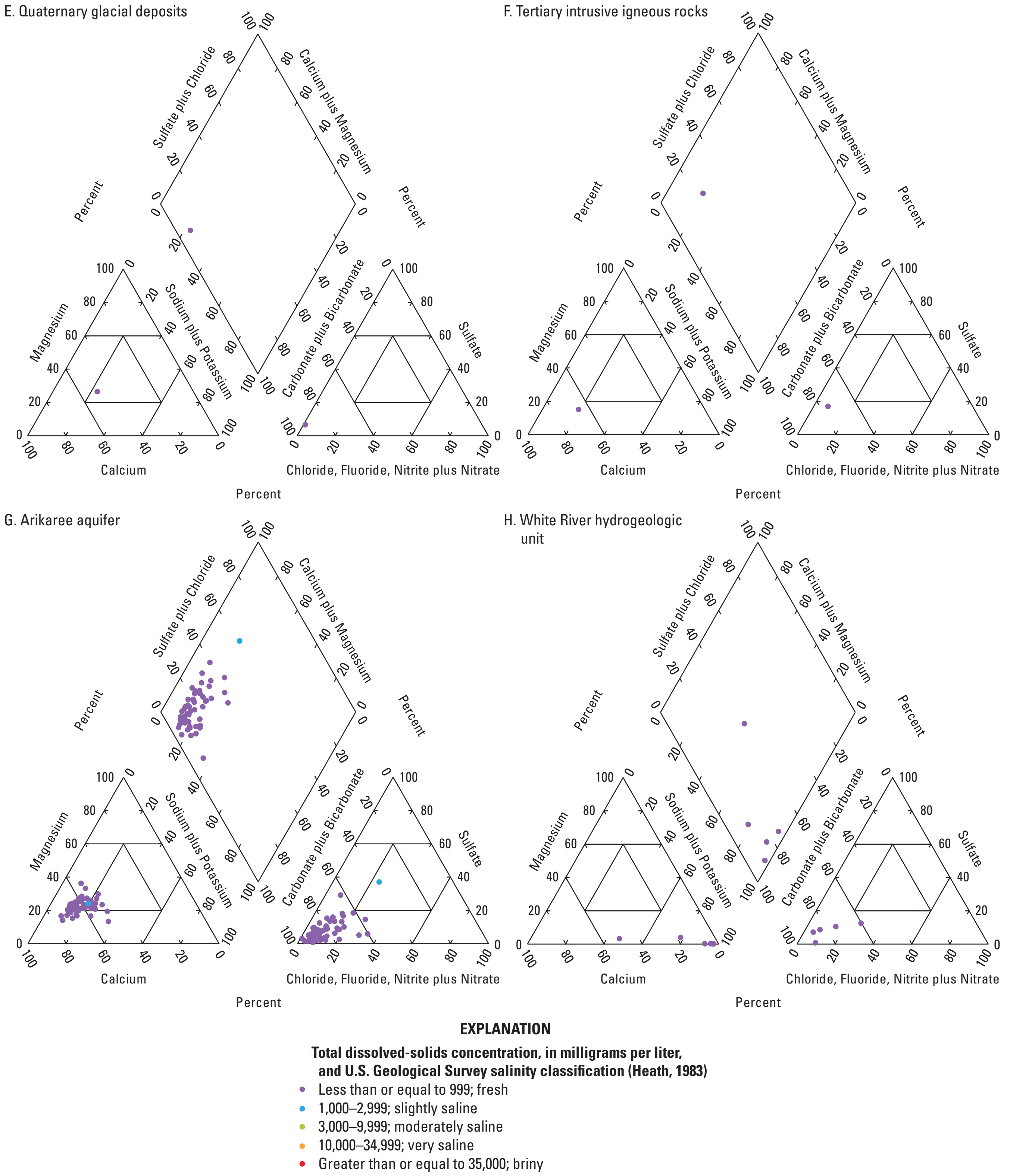
Hydrogeologic unit	Characteristic or constituent	Sample size	Minimum	25th percentile	Median	75th percentile	Maximum
Tensleep aquifer	pH (standard units)	1	--	--	--	--	7.7
	Calcium	1	--	--	--	--	382
	Magnesium	1	--	--	--	--	18.0
	Potassium	1	--	--	--	--	115
	Sodium	1	--	--	--	--	487
	Sodium adsorption ratio (unitless)	1	--	--	--	--	6.6
	Bicarbonate	1	--	--	--	--	464
	Chloride	1	--	--	--	--	340
	Sulfate	1	--	--	--	--	1,320
	Total dissolved solids	1	--	--	--	--	2,891

Appendix I-1

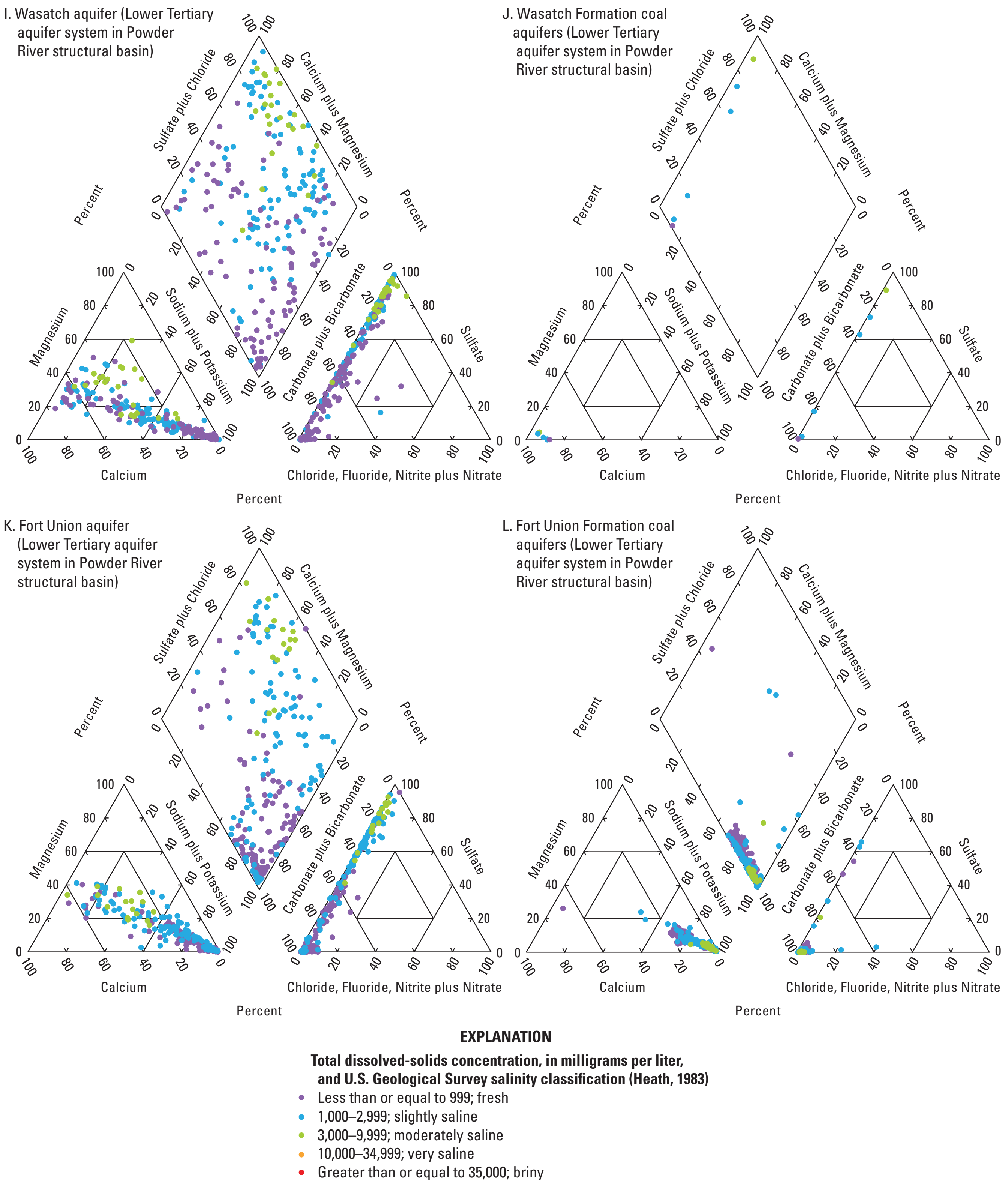
Trilinear diagrams for environmental samples from Cenozoic-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming



Appendix I–1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.



Appendix I–1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued


I. Wasatch aquifer (Lower Tertiary aquifer system in Powder River structural basin)

J. Wasatch Formation coal aquifers (Lower Tertiary aquifer system in Powder River structural basin)

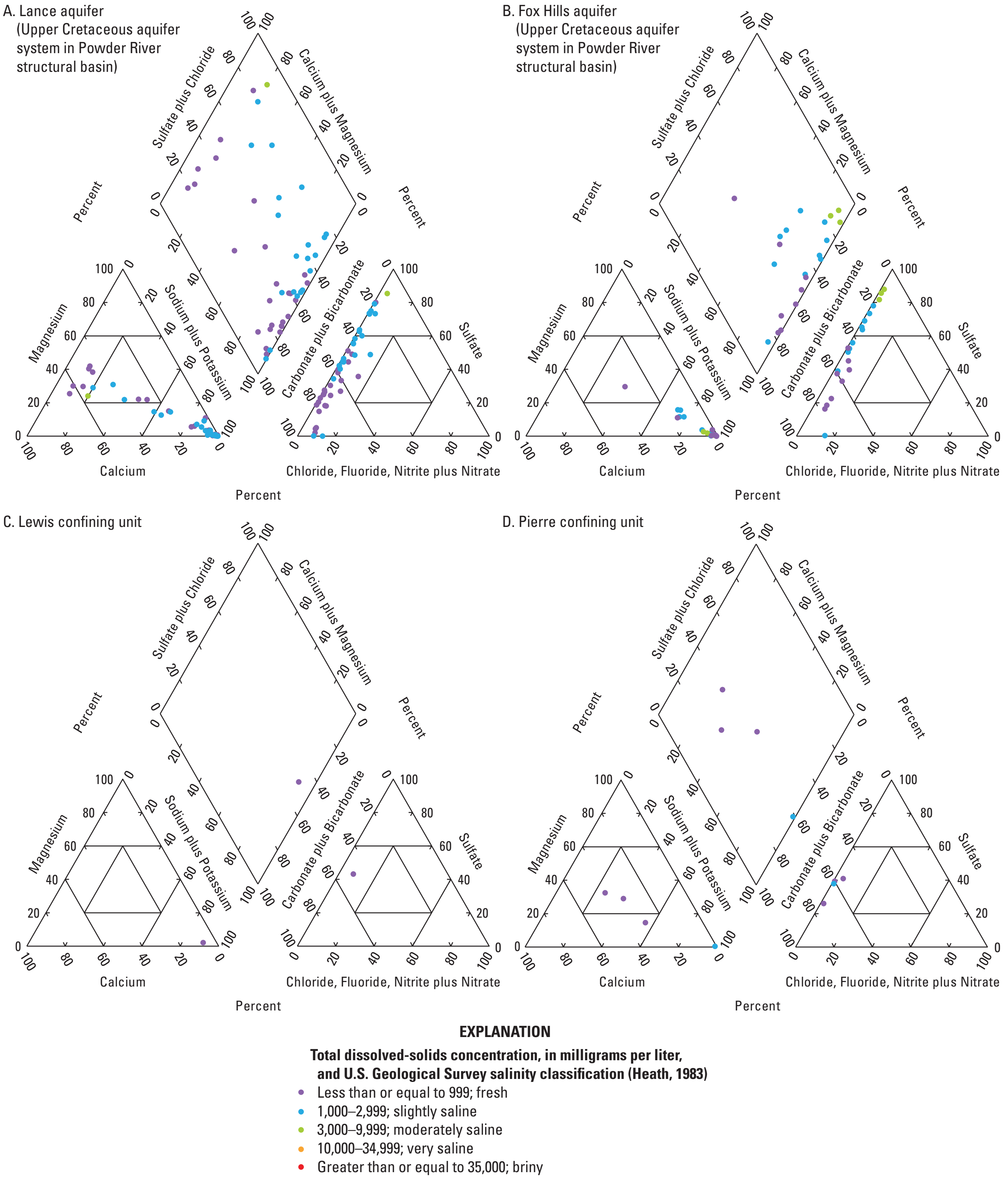
K. Fort Union aquifer (Lower Tertiary aquifer system in Powder River structural basin)

L. Fort Union Formation coal aquifers (Lower Tertiary aquifer system in Powder River structural basin)

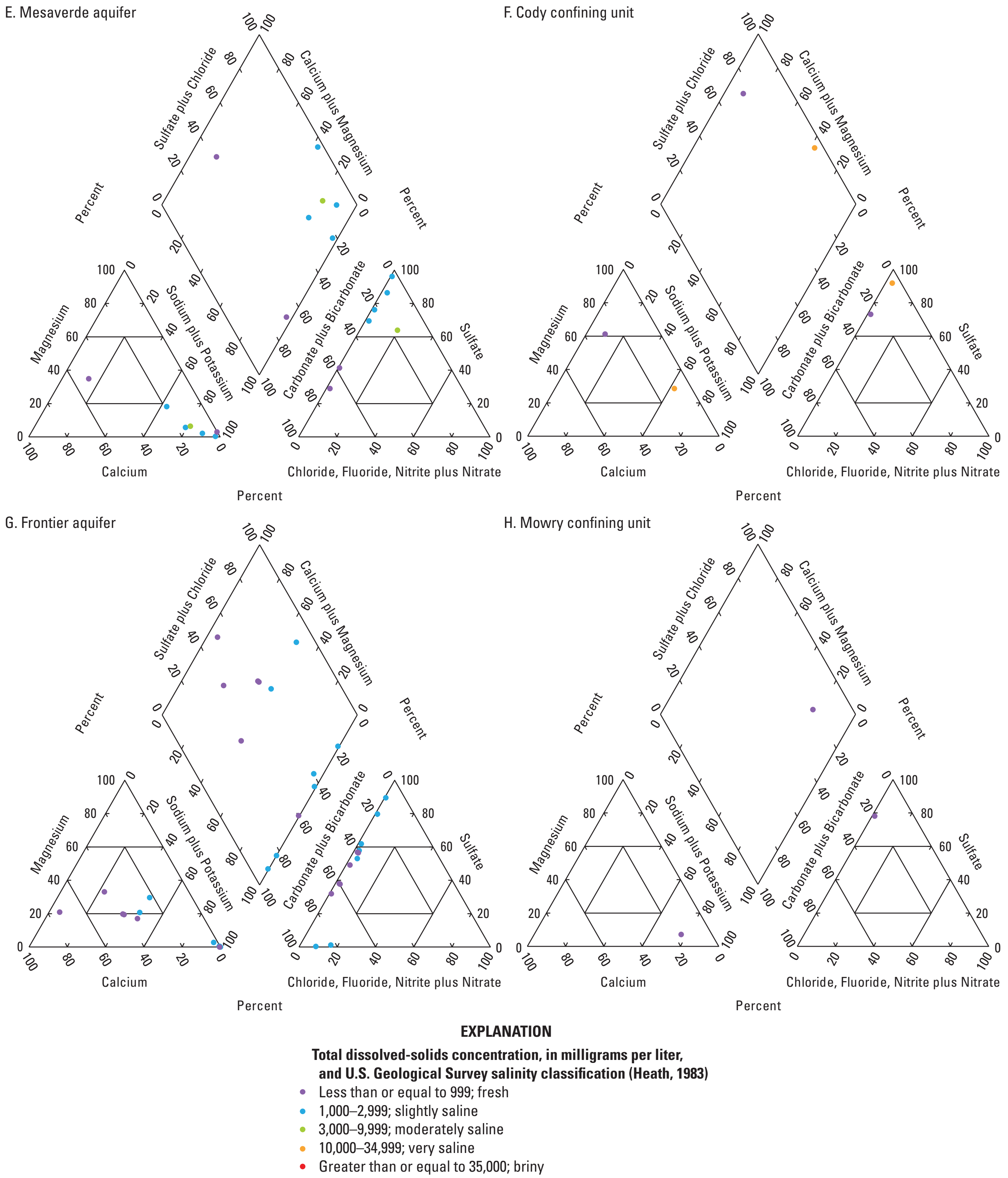
Appendix I–1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued

Appendix I-2

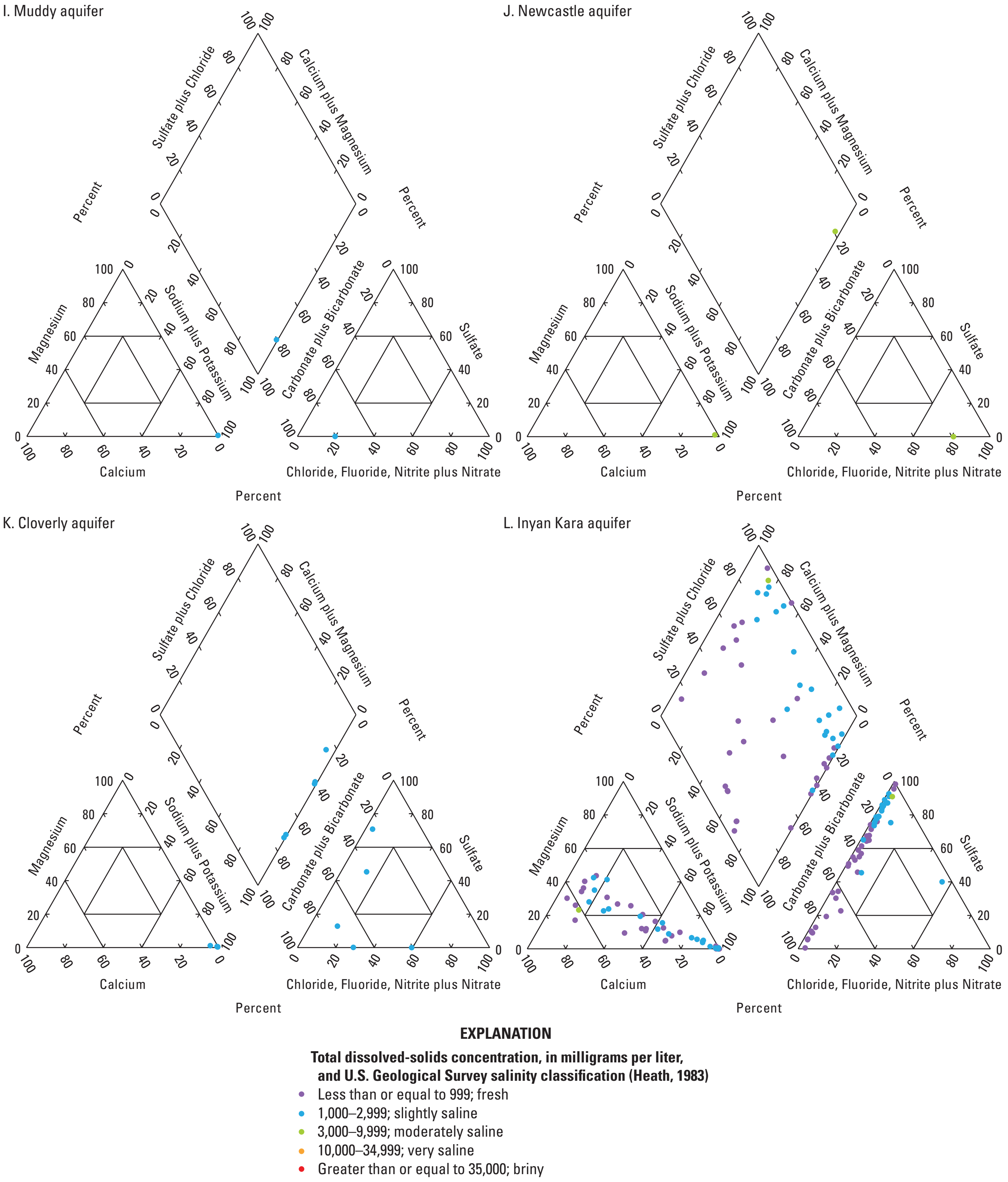
Trilinear diagrams for environmental samples from Mesozoic-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming



Appendix I–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.



Appendix I–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued



I. Muddy aquifer

J. Newcastle aquifer

K. Cloverly aquifer

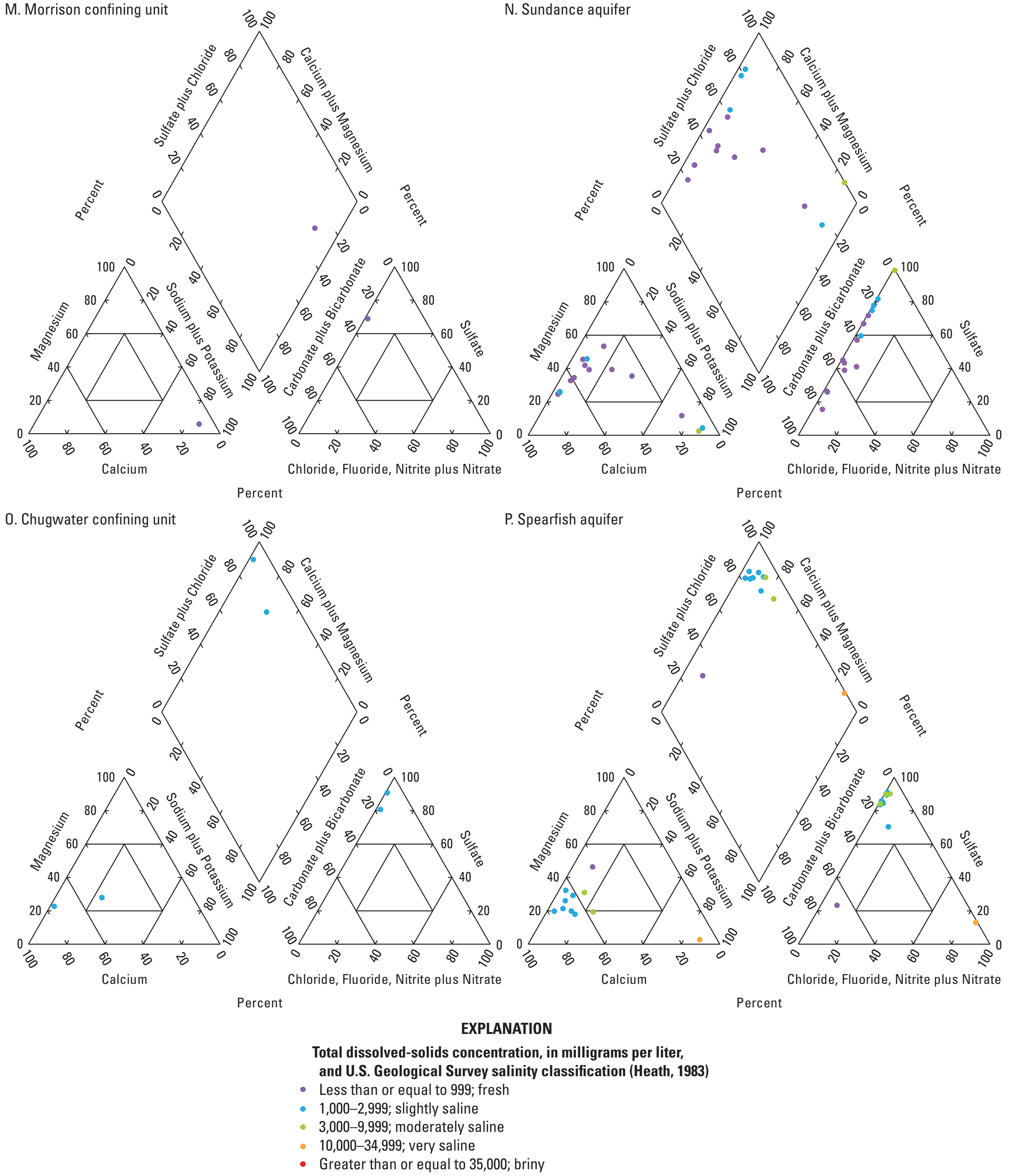
L. Inyan Kara aquifer

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix I–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued



EXPLANATION

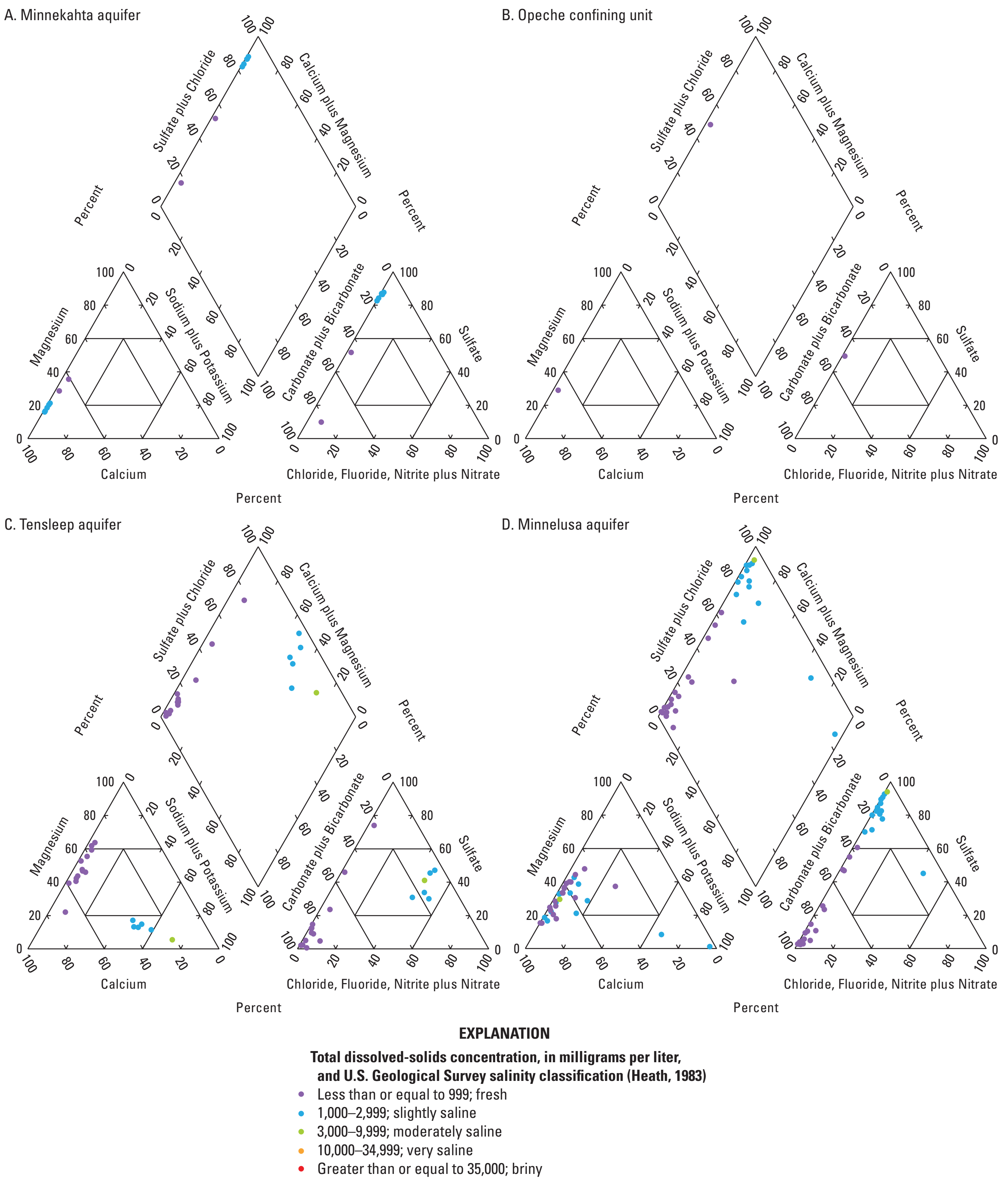
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

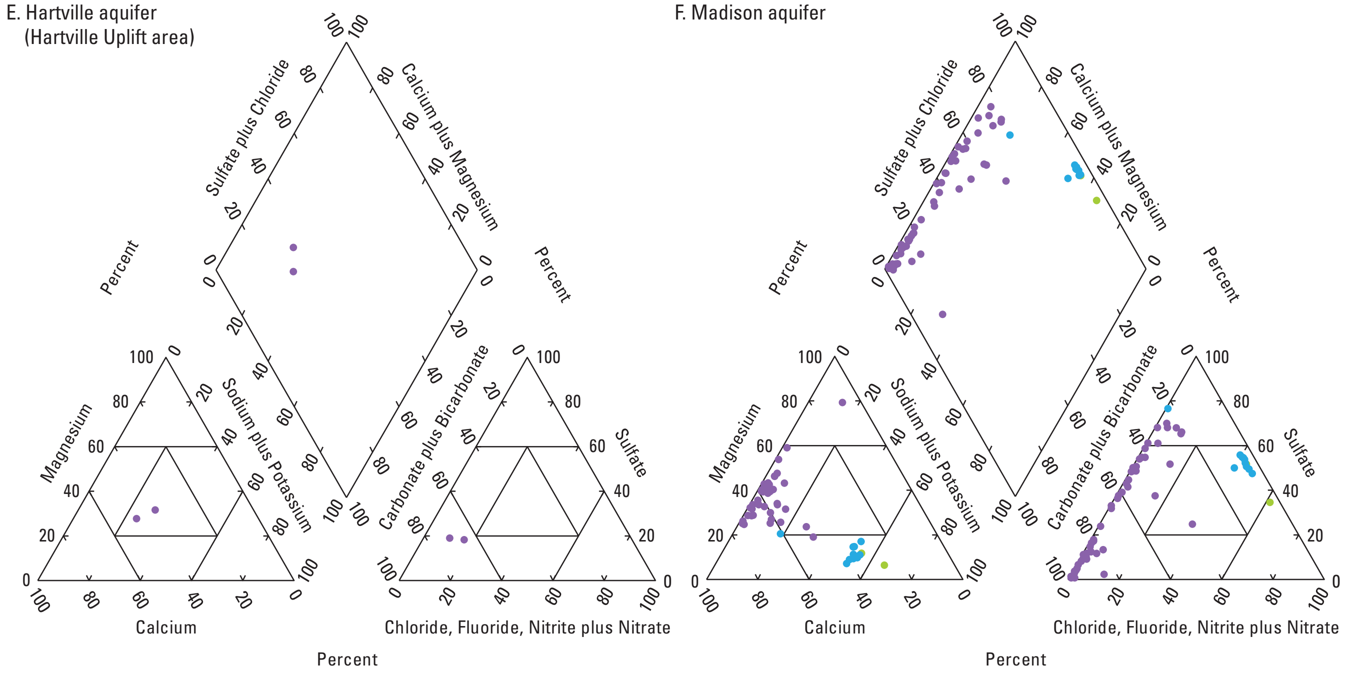
Appendix I–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued

Appendix I-3

Trilinear diagrams for environmental samples from Paleozoic- and Precambrian-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming

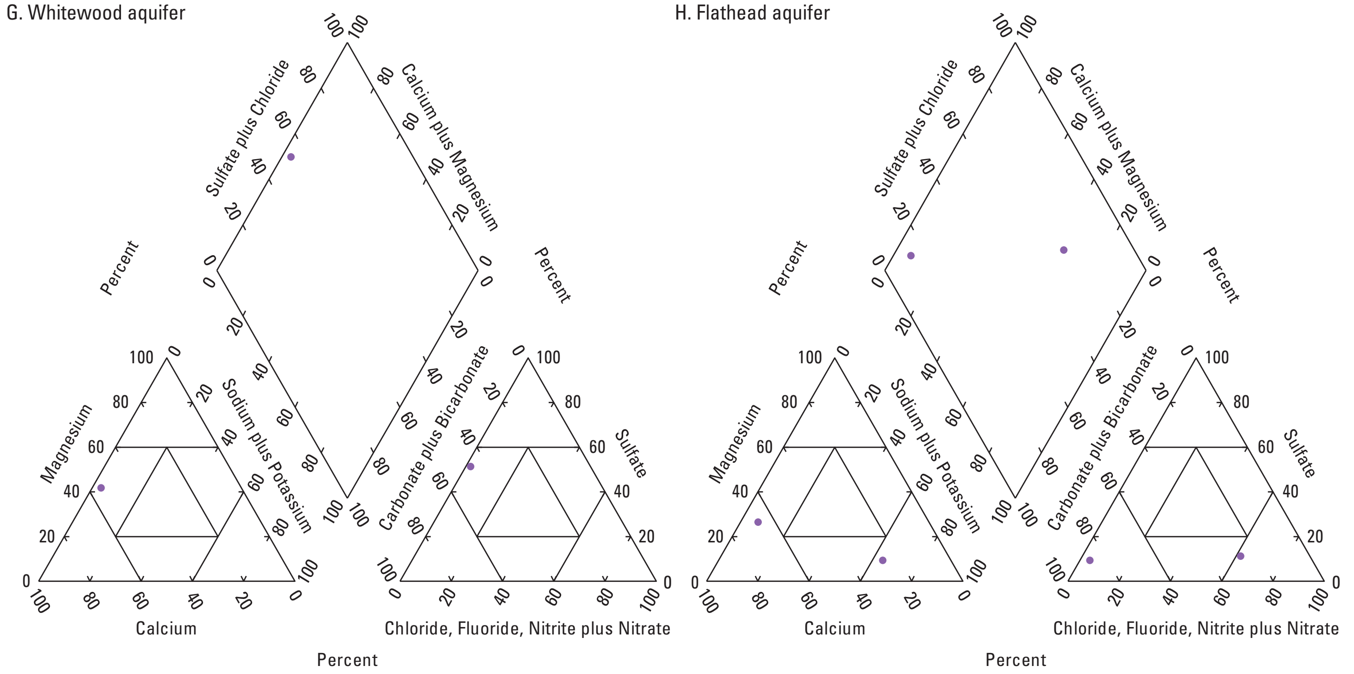


Appendix I–3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.



E. Hartville aquifer (Hartville Uplift area)

F. Madison aquifer



G. Whitewood aquifer

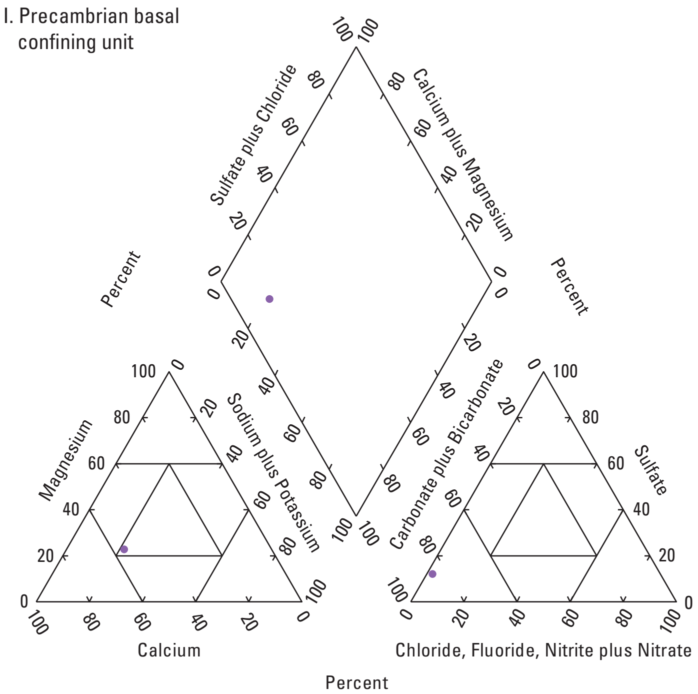
H. Flathead aquifer

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix I–3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued



I. Precambrian basal confining unit

EXPLANATION

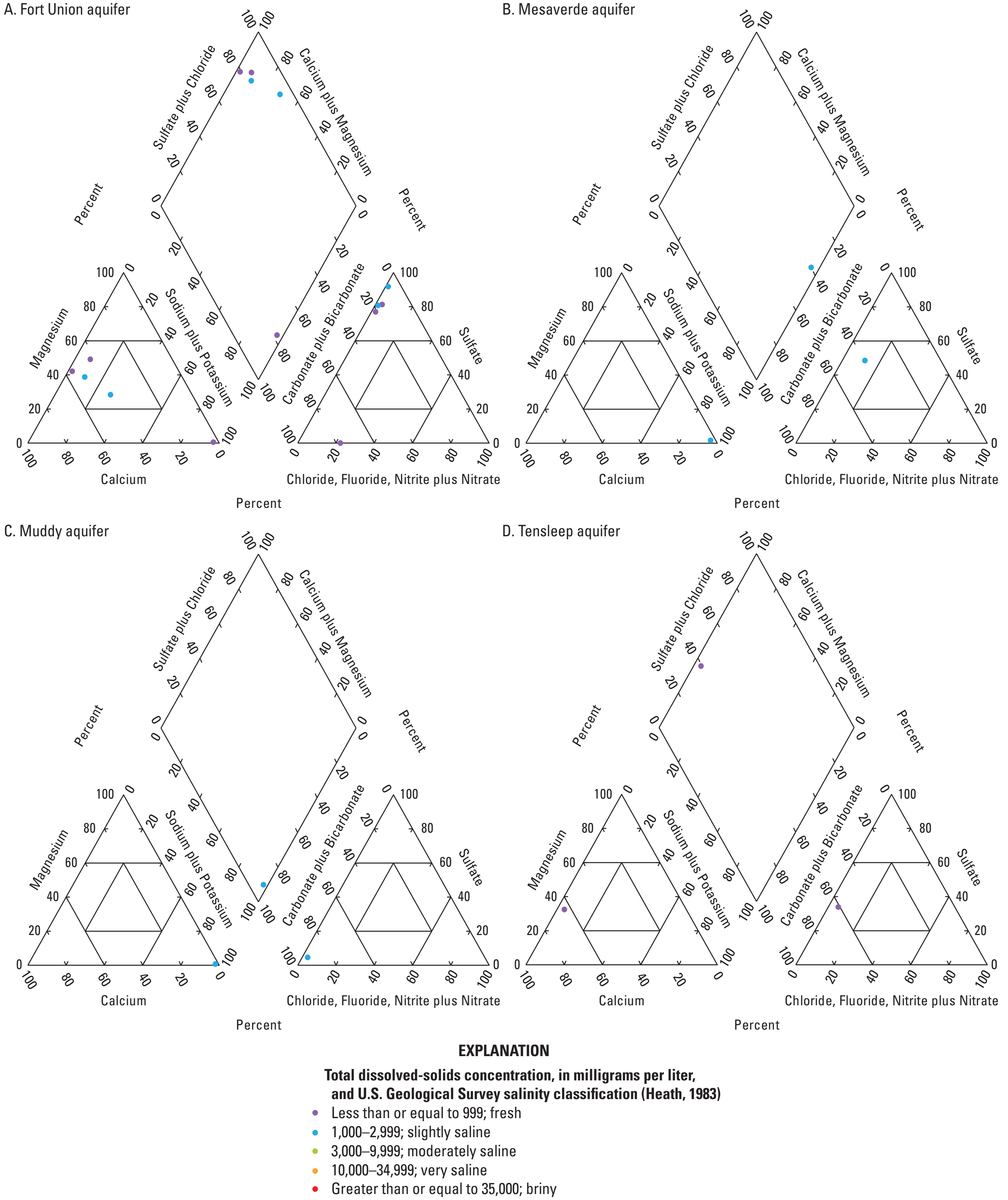
Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix I–3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued

Appendix J

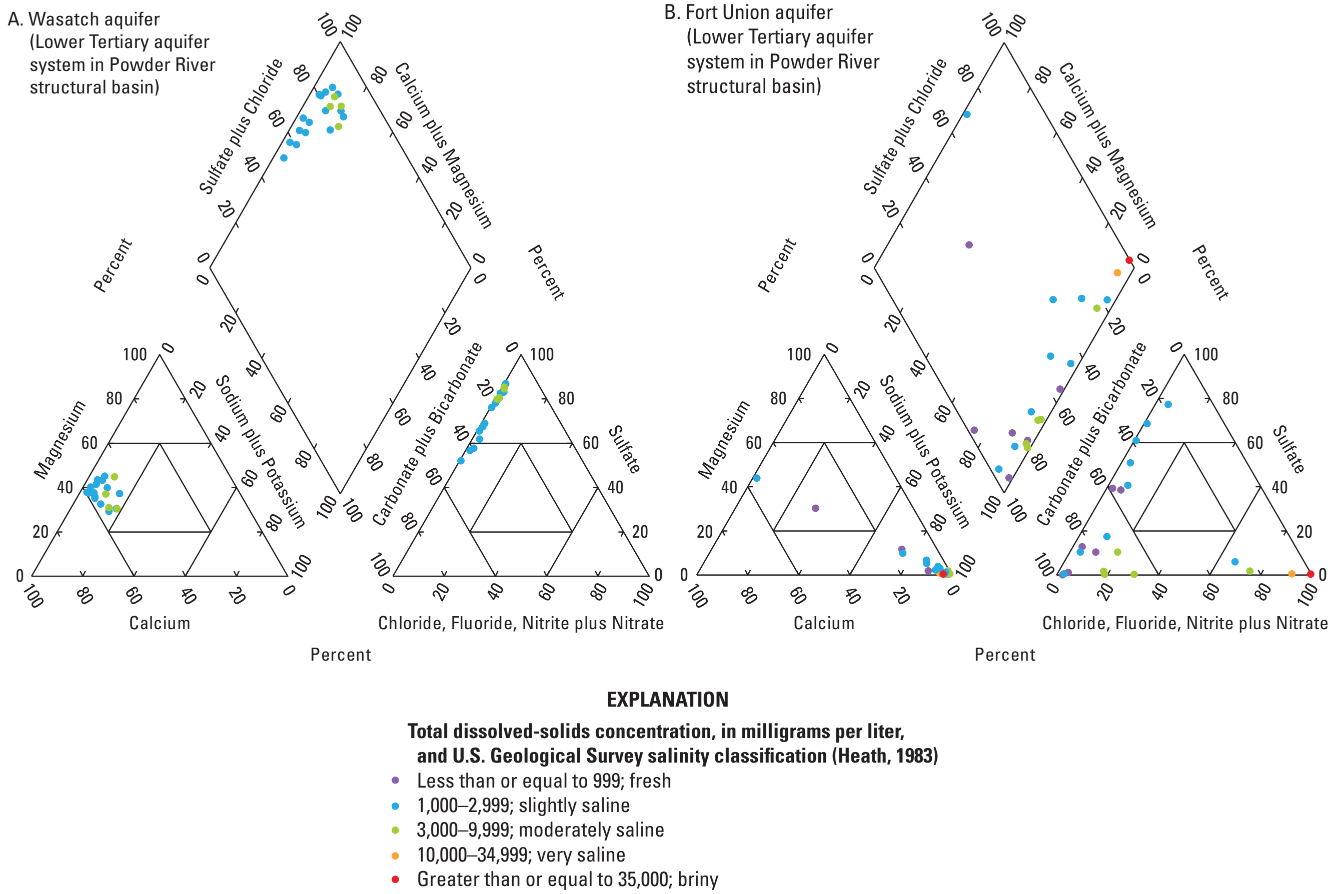
Trilinear diagrams for environmental samples from hydrogeologic units in the Wind River structural basin within the NERB, Wyoming



Appendix J. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental water samples from hydrogeologic units in the Wind River structural basin within the Northeastern River Basins study area, Wyoming.

Appendix K-1

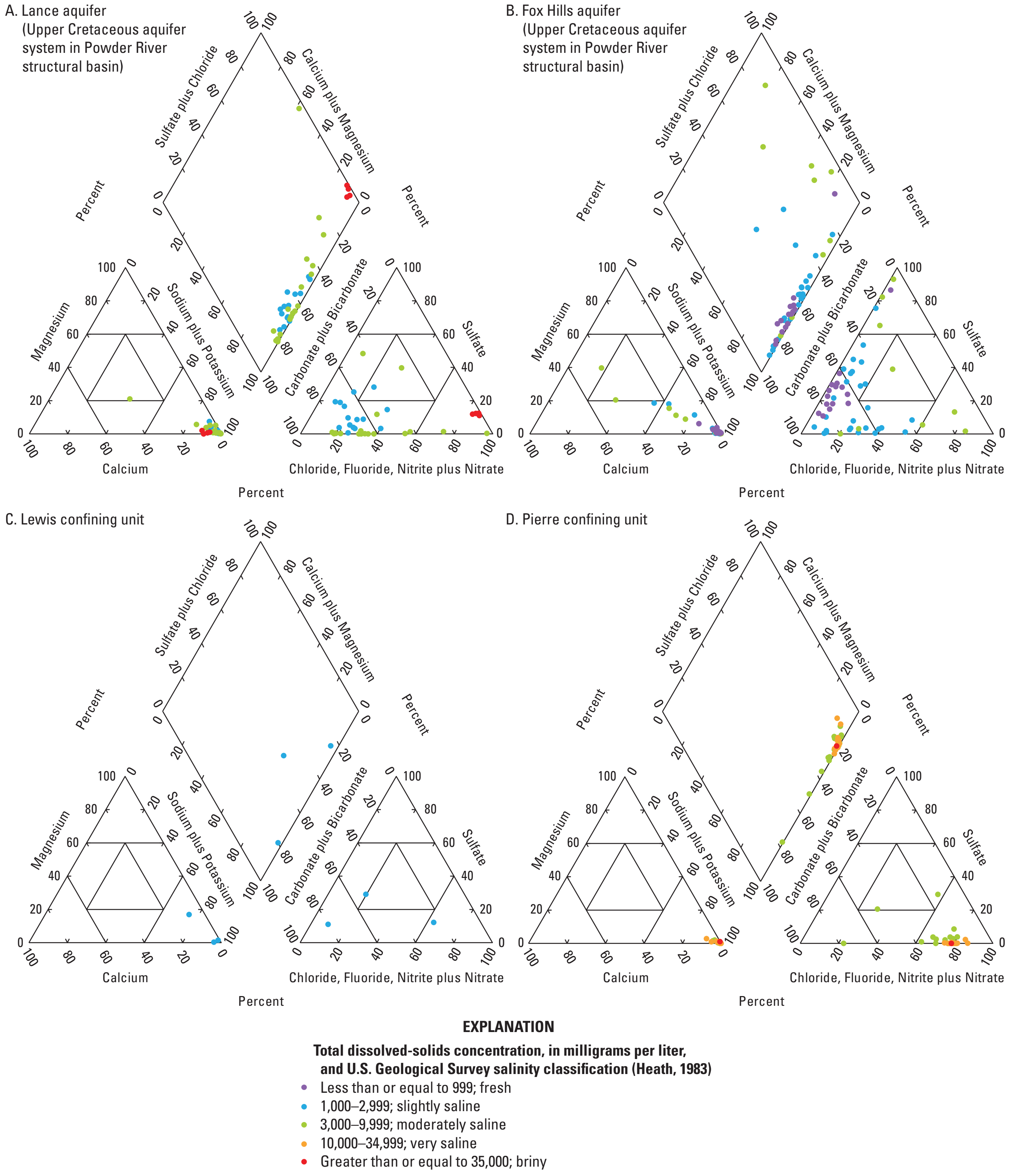
Trilinear diagrams for produced-water samples from Cenozoic-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming



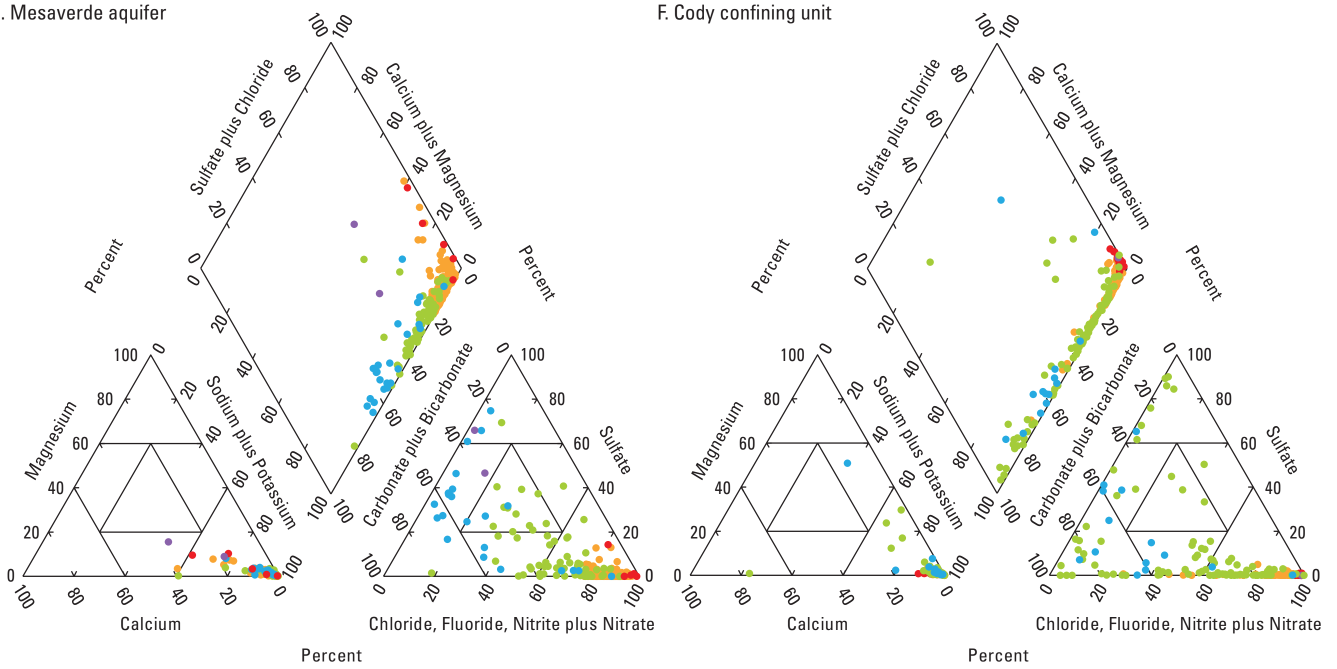
Appendix K–1. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Cenozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.

Appendix K-2

Trilinear diagrams for produced-water samples from Mesozoic-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming

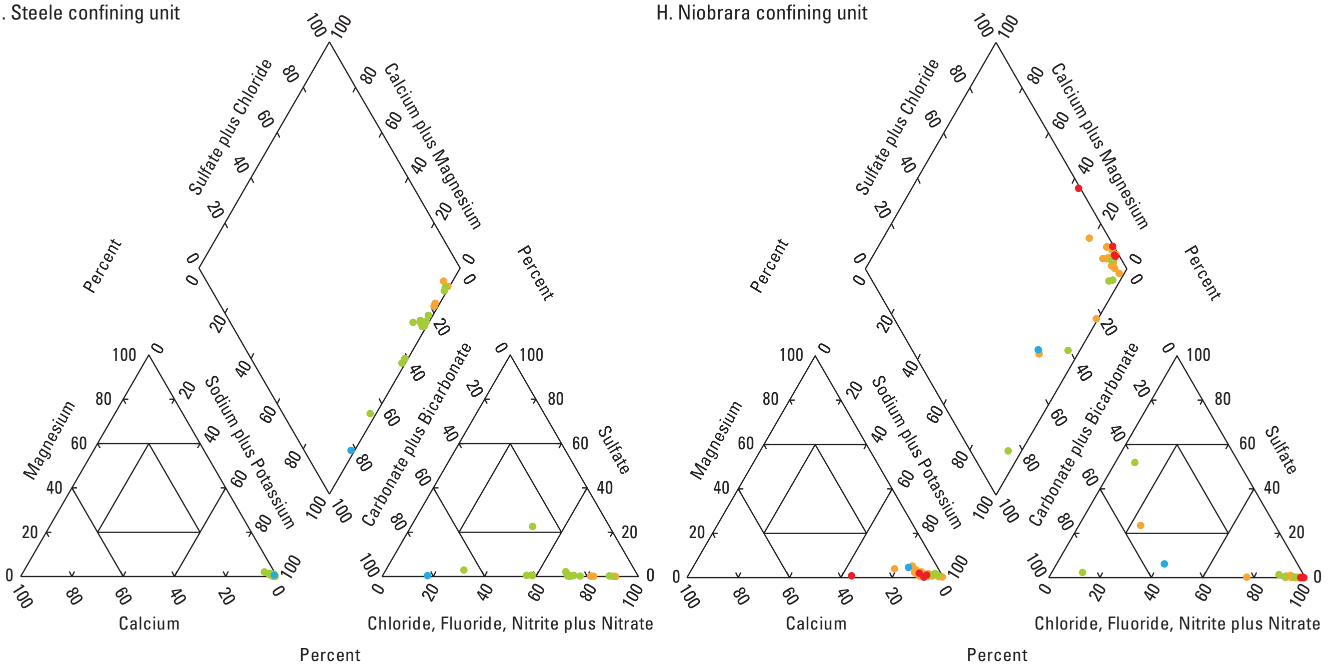


Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.



E. Mesaverde aquifer

F. Cody confining unit



G. Steele confining unit

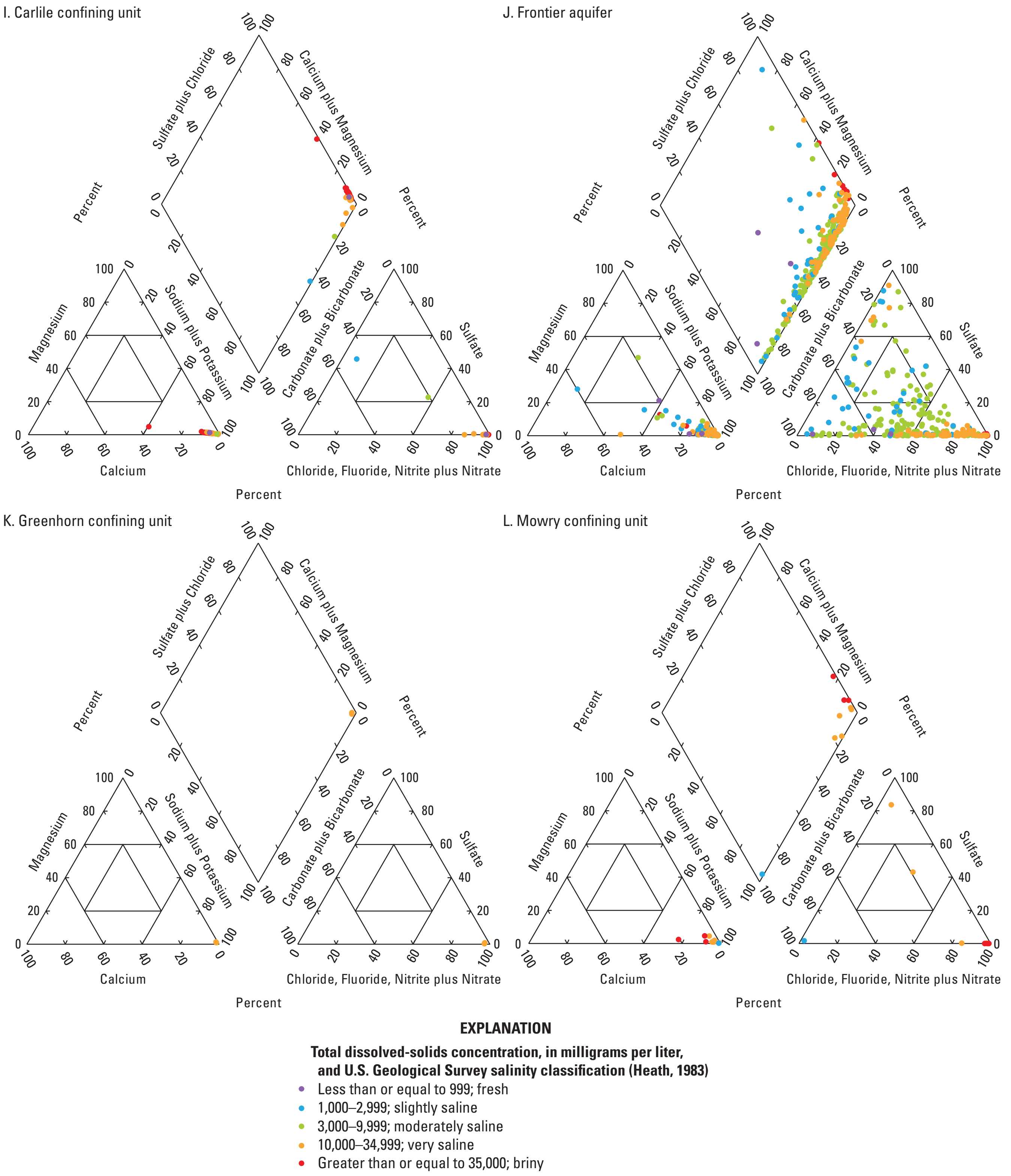
H. Niobrara confining unit

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.–Continued


I. Carlile confining unit

J. Frontier aquifer

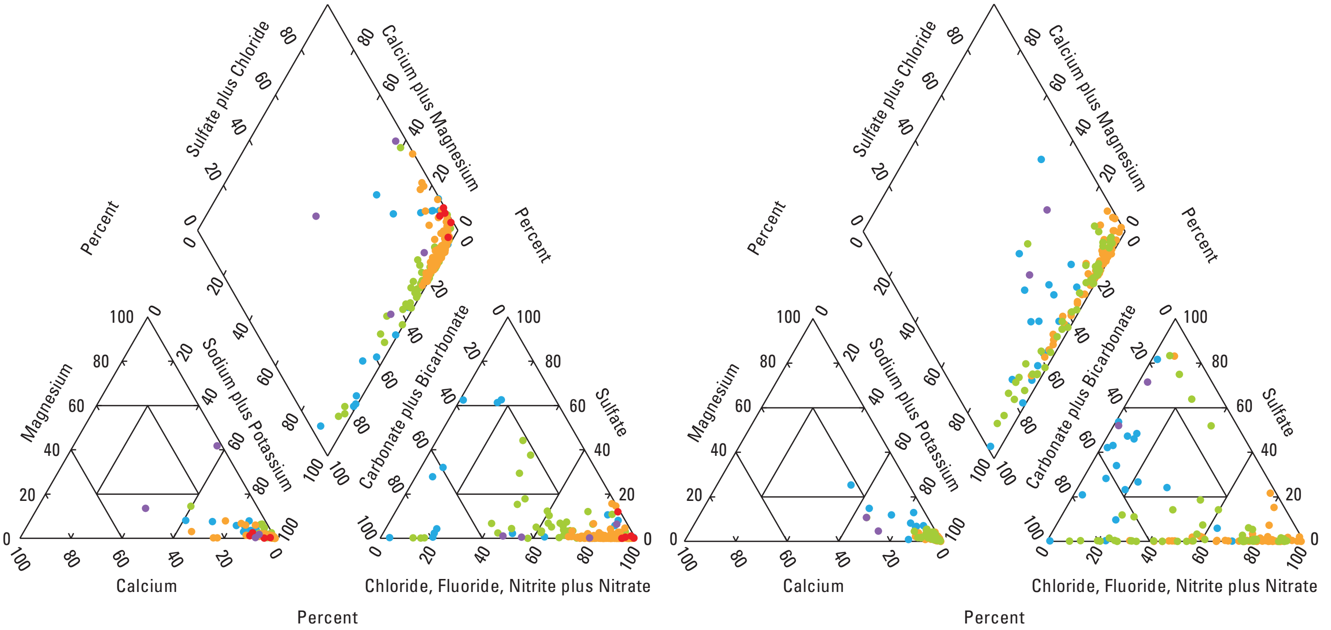
K. Greenhorn confining unit

L. Mowry confining unit

Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued

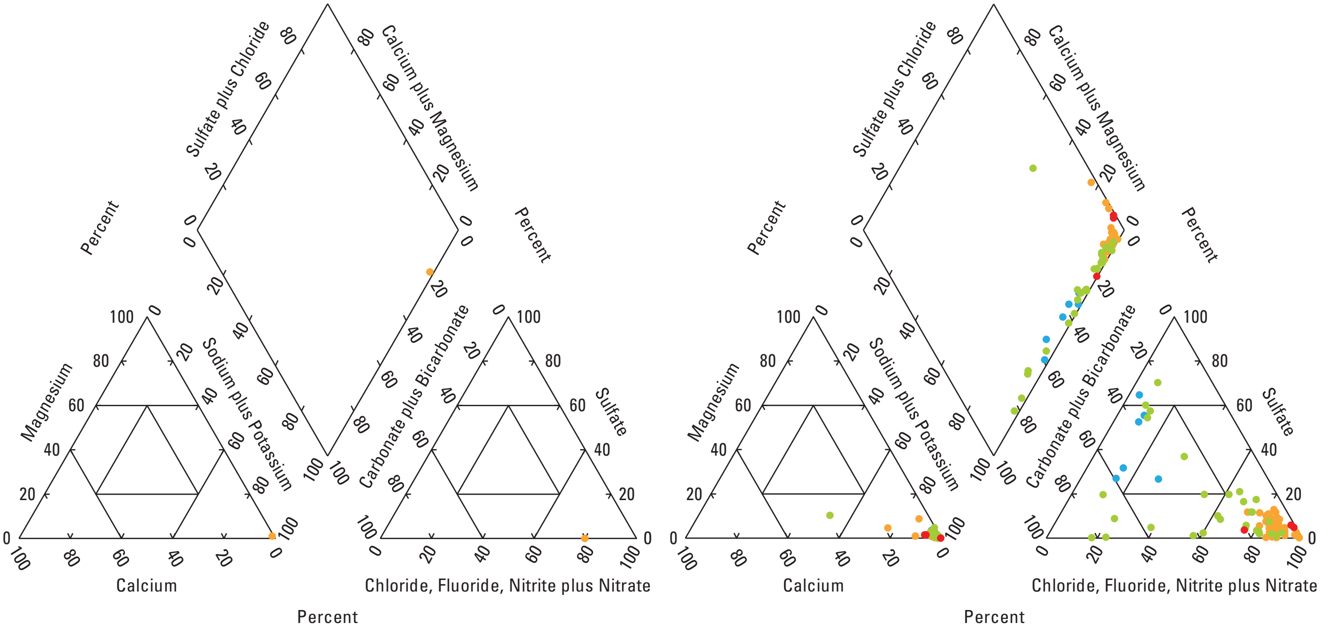
M. Muddy aquifer

N. Newcastle aquifer



O. Skull Creek confining unit

P. Cloverly aquifer

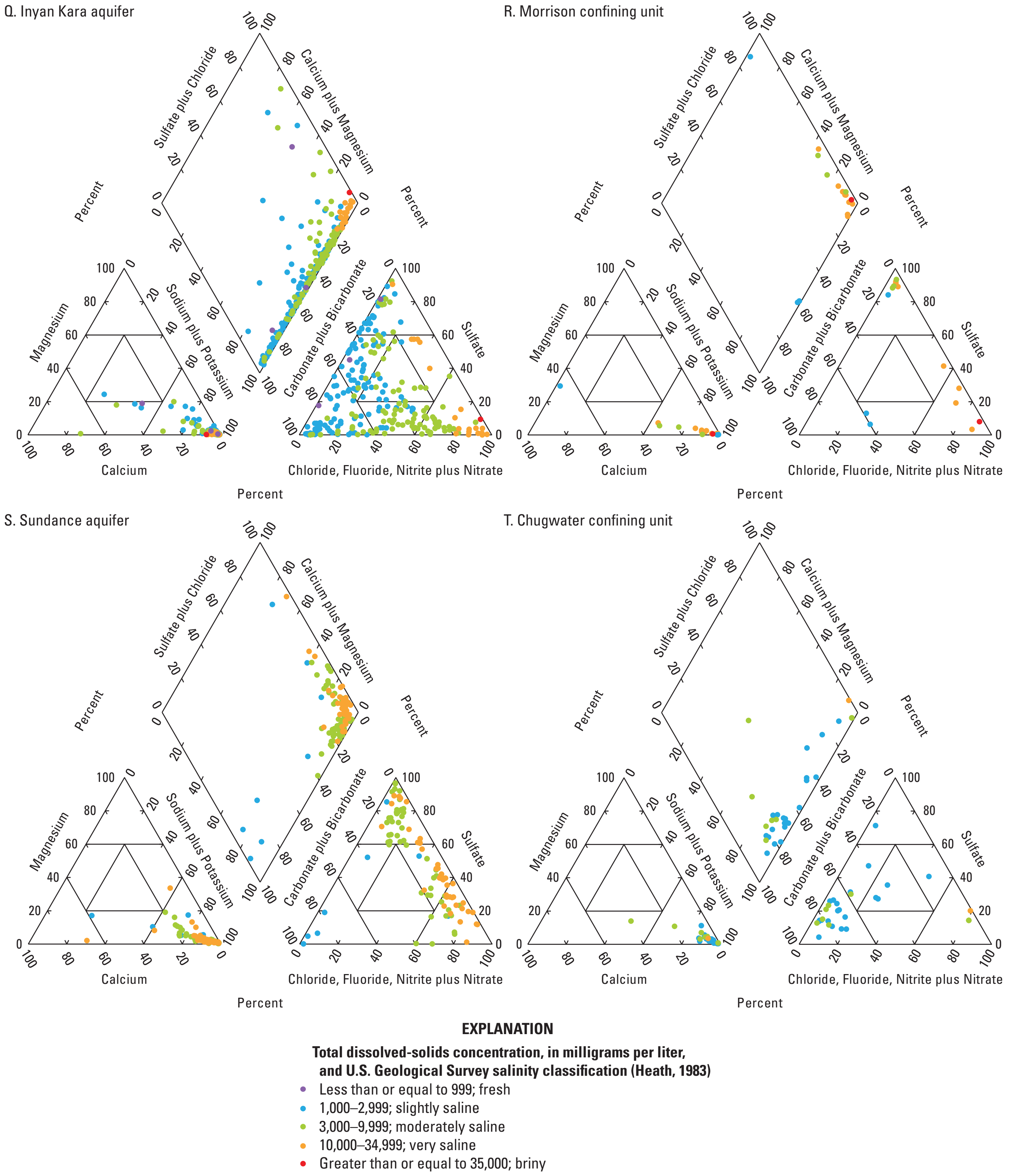


EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

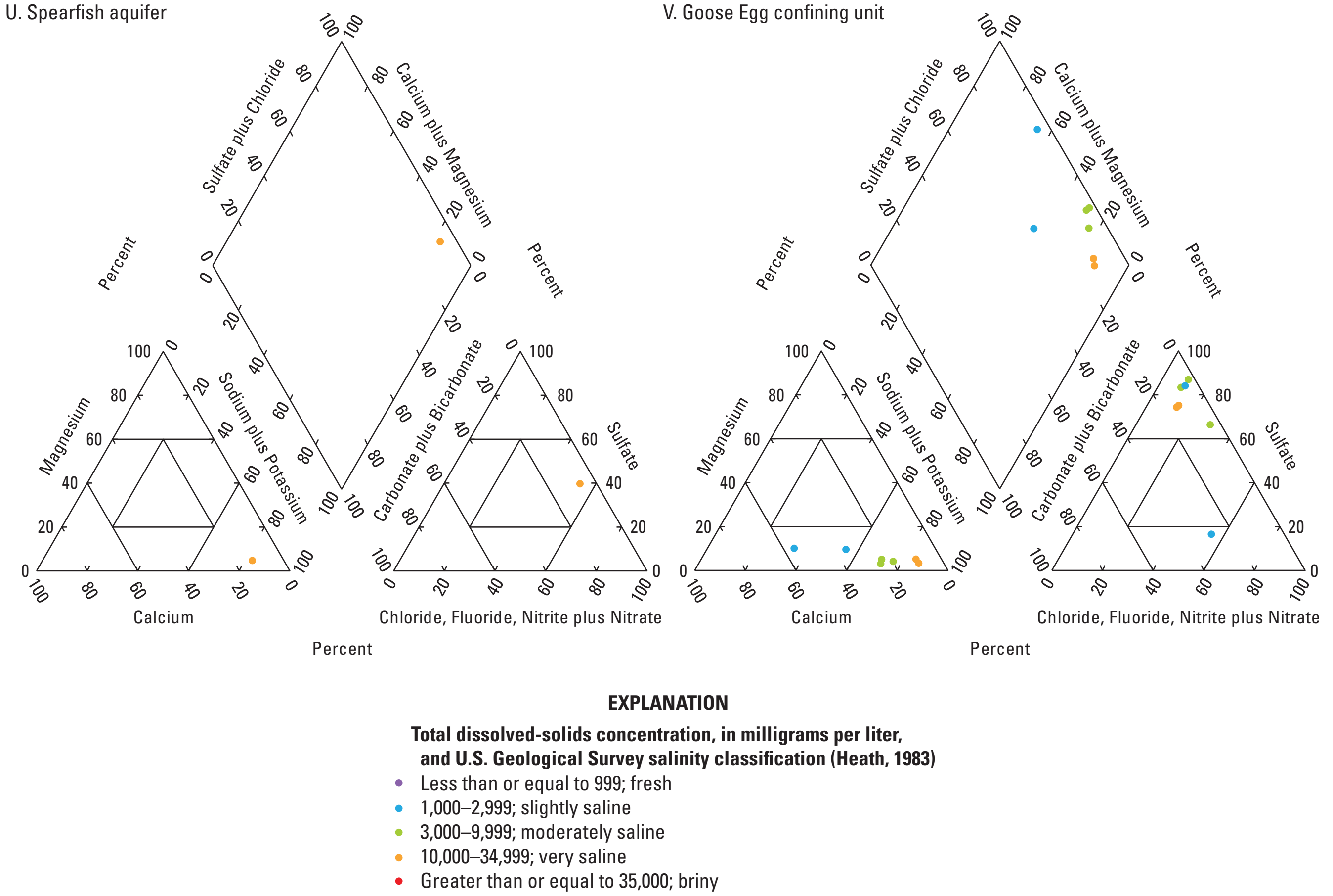
- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.–Continued



Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.–Continued

]



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
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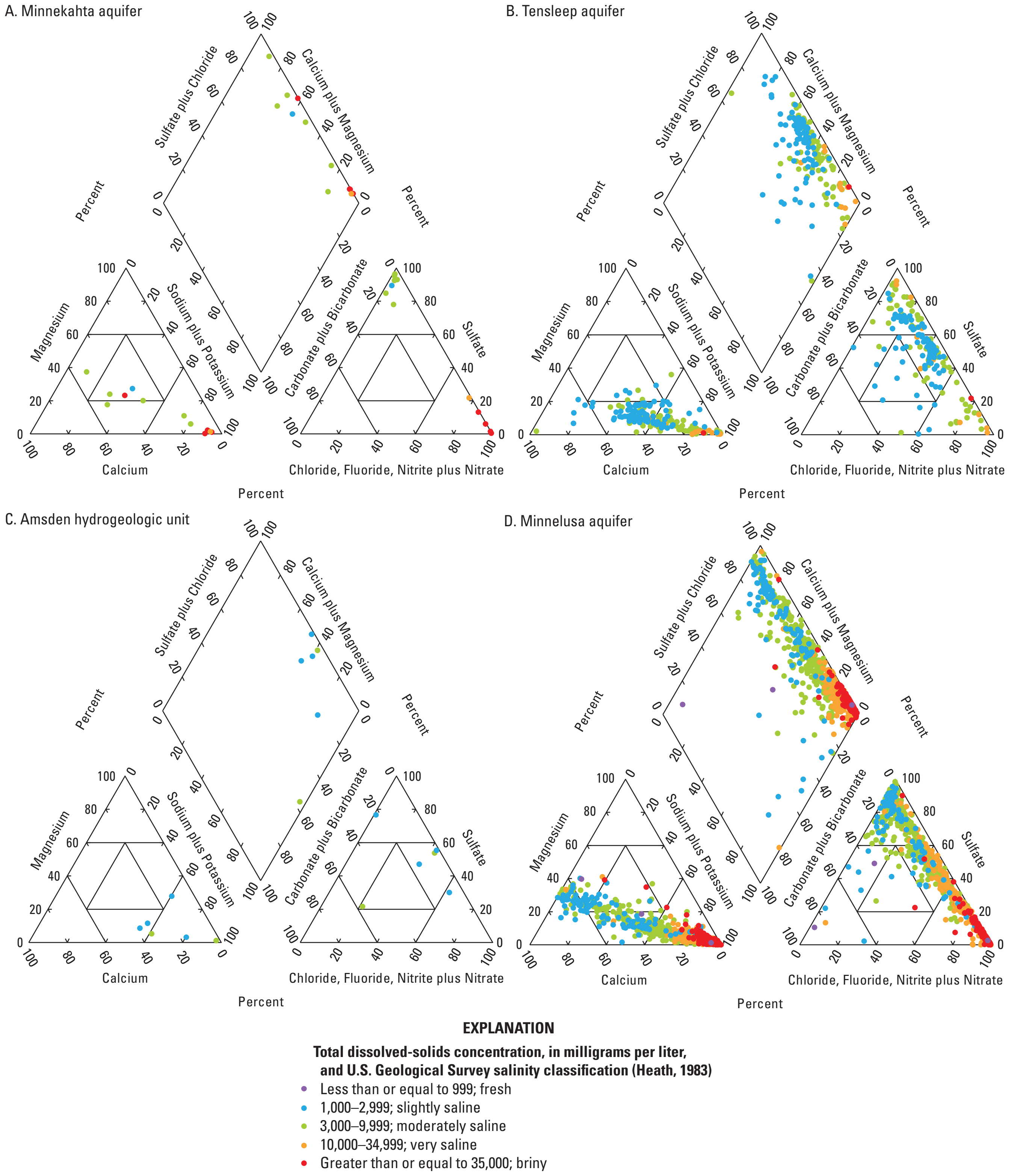
- ● Greater than or equal to 35,000; briny

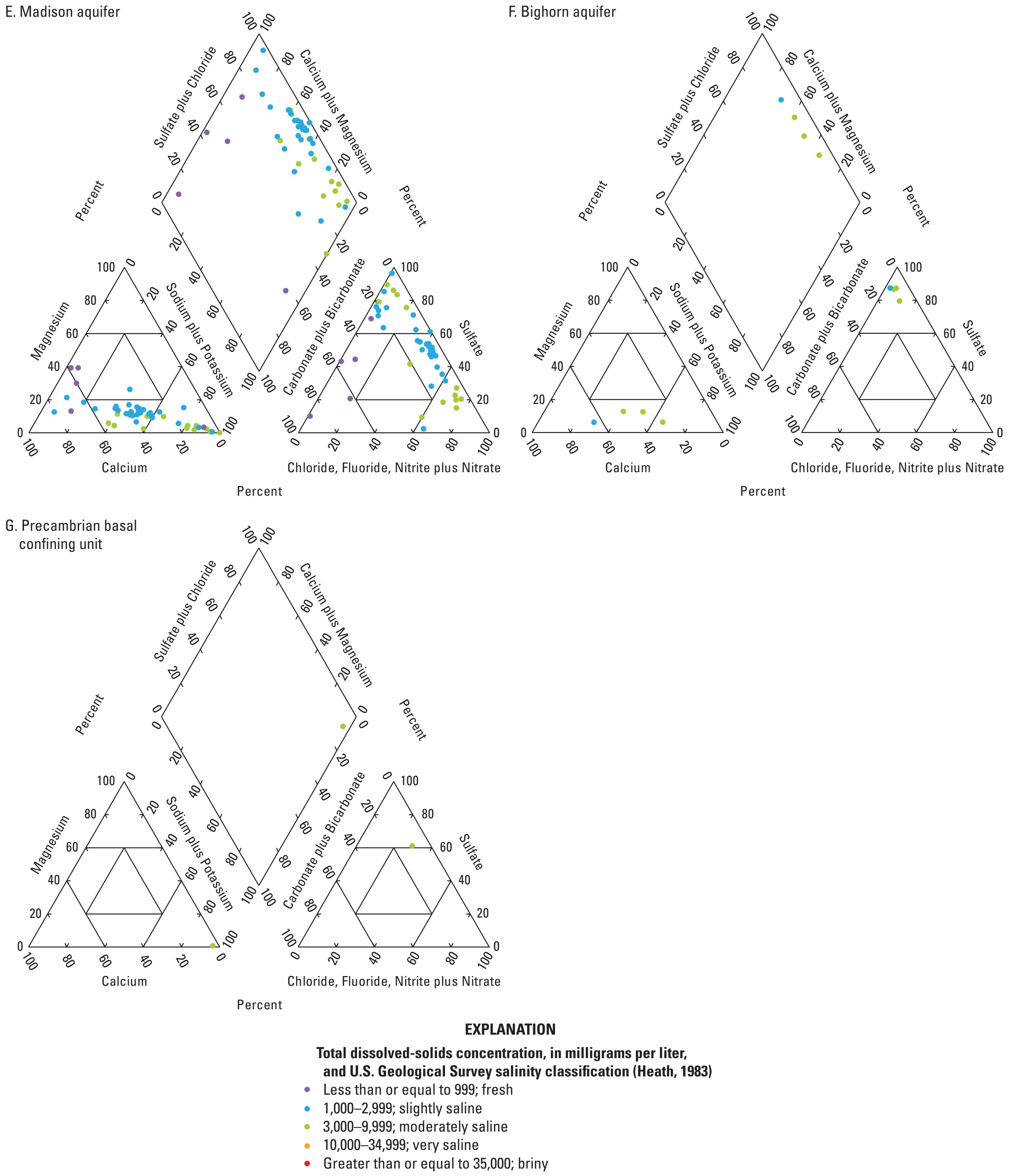
Appendix K–2. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Mesozoic-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.–Continued

Appendix K-3

Trilinear diagrams for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the NERB, excluding Wind River structural basin, Wyoming



Appendix K–3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.


E. Madison aquifer

F. Bighorn aquifer

G. Precambrian basal confining unit

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
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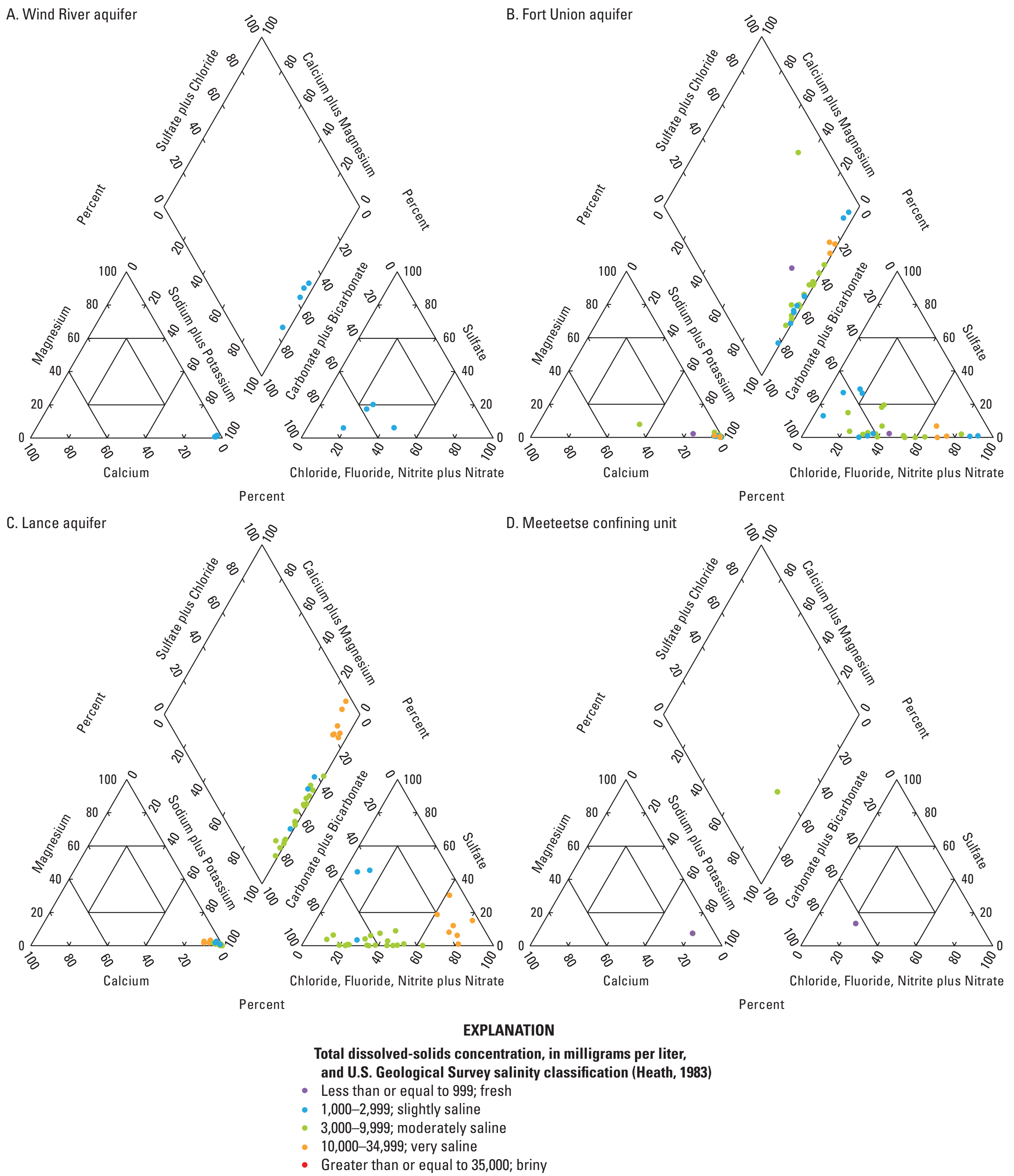
Appendix K–3. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from Paleozoic- and Precambrian-age hydrogeologic units in the Northeastern River Basins study area, excluding Wind River structural basin, Wyoming.—Continued

Appendix L

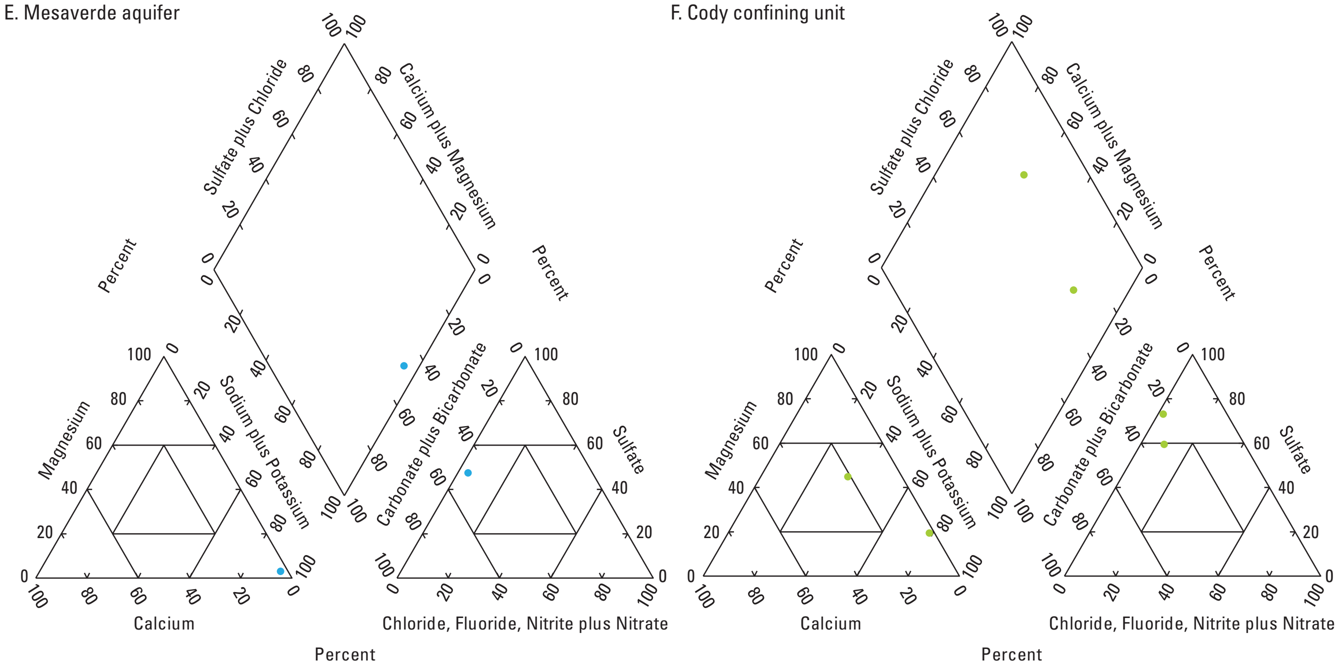
Trilinear diagrams for produced-water samples from hydrogeologic units in the Wind River structural basin within the NERB, Wyoming



Appendix L. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from hydrogeologic units in the Wind River structural basin within the Northeastern River Basins study area, Wyoming.

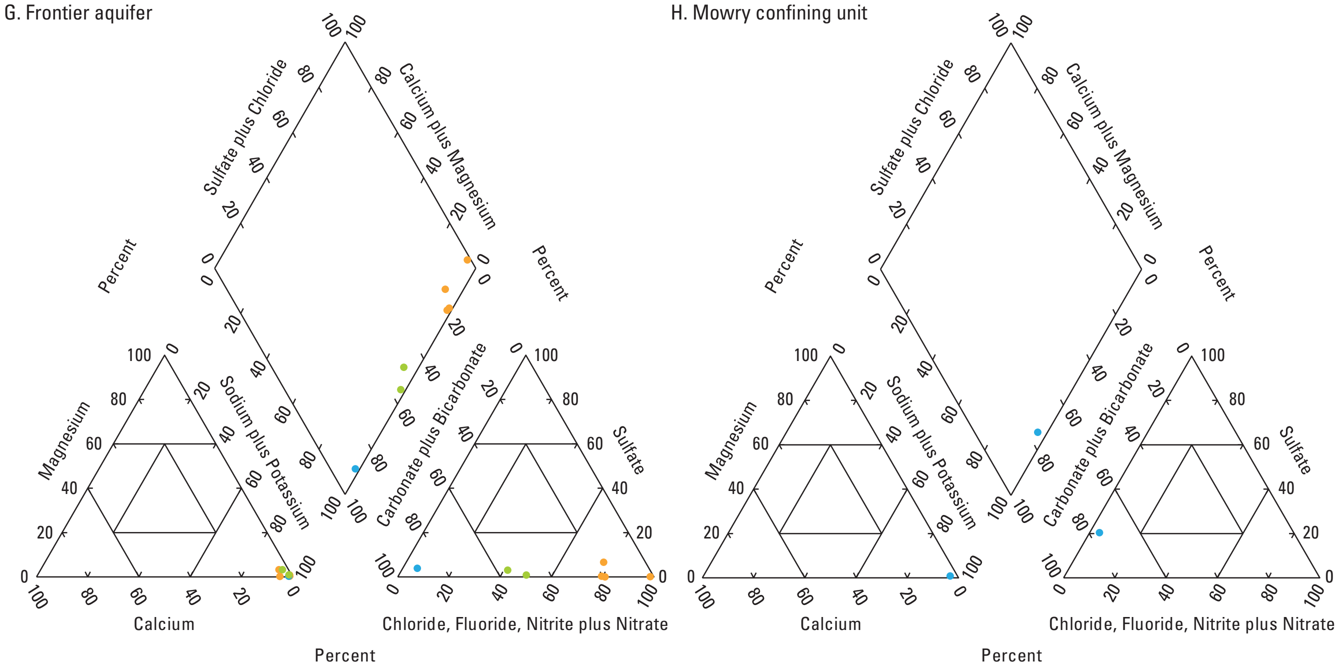
E. Mesaverde aquifer

F. Cody confining unit



G. Frontier aquifer

H. Mowry confining unit



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
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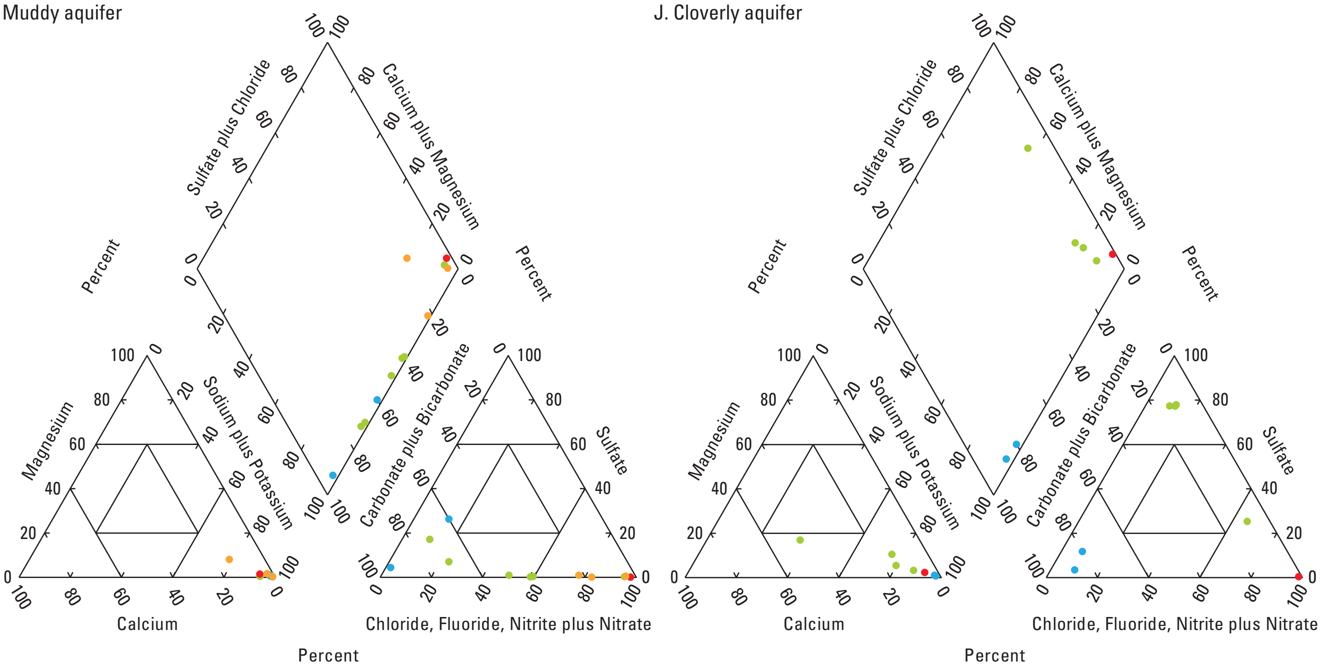
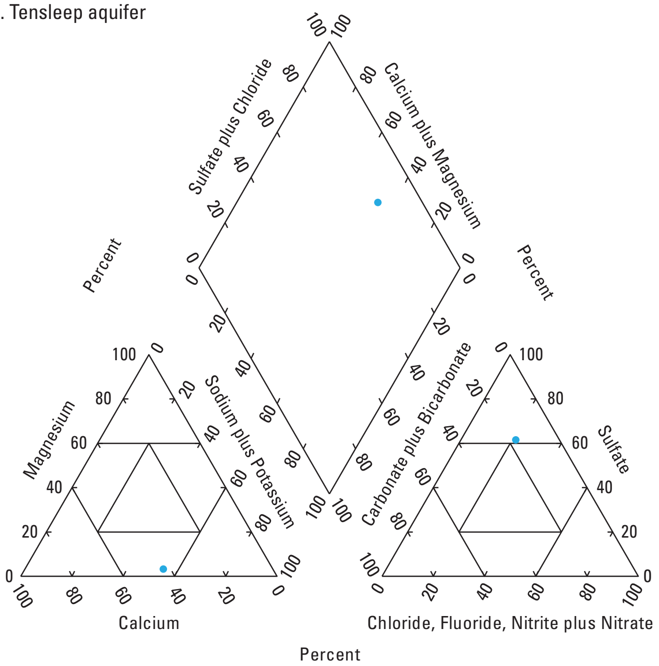
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix L. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from hydrogeologic units in the Wind River structural basin within the Northeastern River Basins study area, Wyoming.—Continued


I. Muddy aquifer

J. Cloverly aquifer

K. Tensleep aquifer



EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

● Less than or equal to 999; fresh

● 1,000–2,999; slightly saline

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● 10,000–34,999; very saline

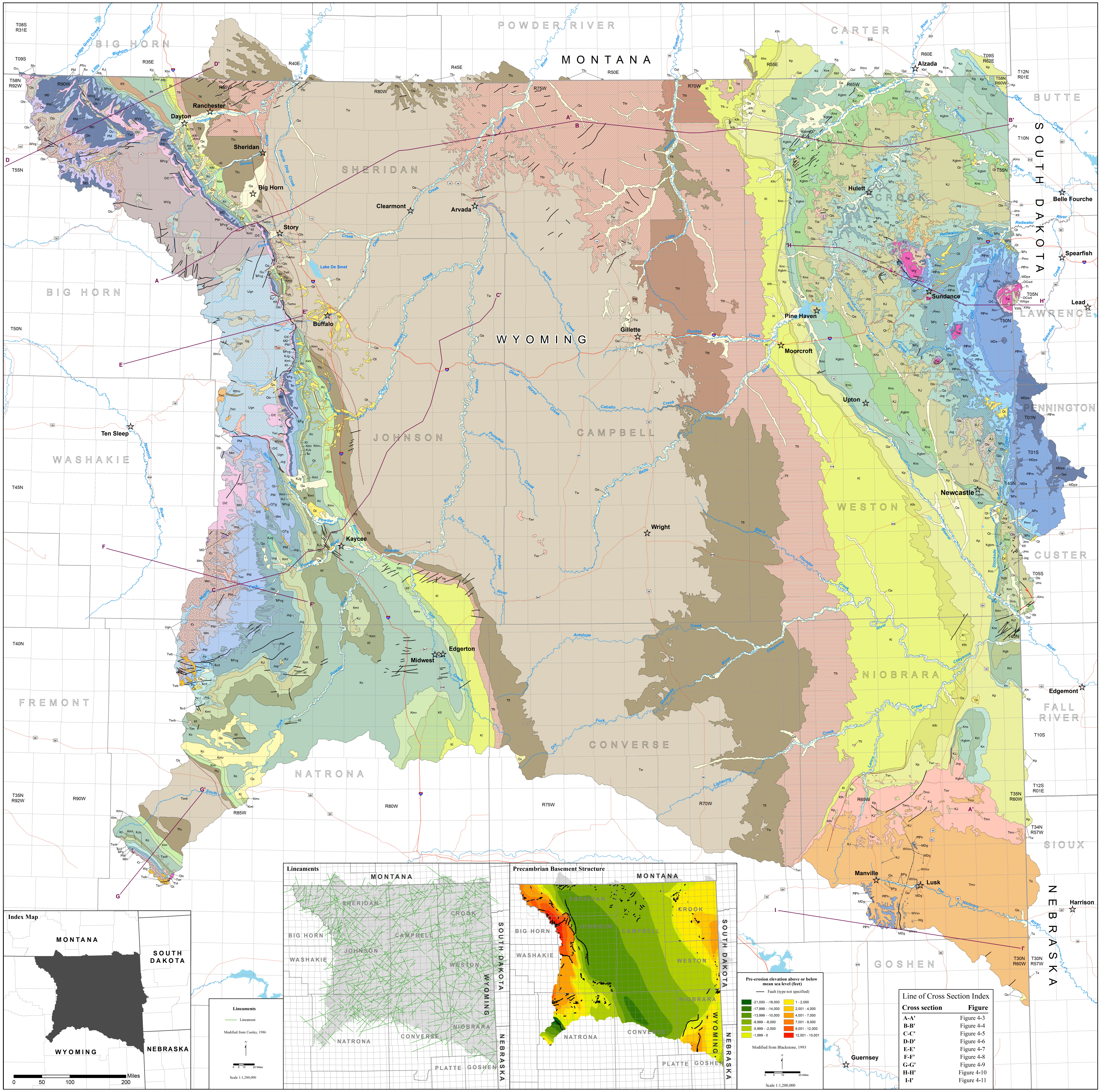
● Greater than or equal to 35,000; briny

Appendix L. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced-water samples from hydrogeologic units in the Wind River structural basin within the Northeastern River Basins study area, Wyoming.—Continued

WYOMING STATE GEOLOGICAL SURVEY
Erin A. Campbell, Director and State Geologist
Laramie, Wyoming

Interpreting the past, providing for the future

Powder, Tongue, and Northeast River Basins Plan II - Available Groundwater Determination Technical Memorandum



Lineaments

Lineament

Modified from Cooley, 1986

0 5 10 20 Miles

Scale 1:1,200,000

Pre-erosion elevation above or below mean sea level (feet)

Fault (type not specified)

🟩	-21,000 - -18,000	🟨	1 - 2,000
🟩	-17,999 - -14,000	🟨	2,001 - 4,000
🟩	-13,999 - -10,000	🟧	4,001 - 7,000
🟩	-9,999 - -6,000	🟧	7,001 - 9,000
🟩	-5,999 - -2,000	🟥	9,001 - 12,000
🟨	-1,999 - 0	🟥	12,001 - 15,001

Modified from Blackstone, 1993

0 5 10 20 Miles

Scale 1:1,200,000

Line of Cross Section Index

Cross section	Figure
A-A'	Figure 4-3
B-B'	Figure 4-4
C-C'	Figure 4-5
D-D'	Figure 4-6
E-E'	Figure 4-7
F-F'	Figure 4-8
G-G'	Figure 4-9
H-H'	Figure 4-10
I-I'	Figure 4-11

Plate I

Bedrock Geology - Powder, Tongue, and Northeast River Basins

Bedrock Geology - Powder, Tongue, and Northeast River Basins
Wyoming, Montana, Nebraska, and South Dakota

compiled by
Jacob D. Carnes, James E. Stafford, Andrea M. Loveland, and James R. Rodgers

Magnetic Declination = 9.03° E
at center of map
(November 5, 2019)

0 5 10 15 20 25 30 Miles

Scale 1:400,000

Explanation

90	Interstate highway
59	U.S. highway
116	State highway
—---	Normal fault—dotted where concealed
—---	Thrust fault—dotted where concealed
A—A′	Line of cross section
☆	City or town
☐	Township boundary
☐	County boundary
☐	State boundary
▬	Lake or reservoir
~	River or creek

Bedrock Geology

Wyoming Geologic Units

CENOZOIC

Quaternary

Qa	Alluvium and colluvium
Qt	Gravel, pediment, and fan deposits
Qg	Glacial deposits
Qls	Landslide deposits
Qs	Dune sand and loess
Qu	Surficial deposits, undivided

Quaternary-Tertiary

QTg	Terrace gravels

Tertiary

Tmu	Upper Miocene rocks
Tml	Lower Miocene rocks
Tmo	Lower Miocene and Upper Oligocene rocks
Twr	White River Formation
Tid	Dacite and quartz latite intrusive and extrusive igneous rocks
Twb	Wagon Bed Formation
Tai	Alkalic intrusive and extrusive igneous rocks
Tw	Wasatch Formation
Twmo	Moncrief Member of the Wasatch Formation
Twk	Kingsbury Conglomerate Member of the Wastach Formation
Tie	Intrusive and extrusive igneous rocks
Twdr	Wind River Formation
Tim	Indian Meadows Formation
Tfu	Fort Union Formation
Tftr	Tongue River Member of the Fort Union Formation
Tfl	Lebo Member of the Fort Union Formation
Tft	Tullock Member of the Fort Union Formation
Tftl	Tongue River and Lebo members of the Fort Union Formation
Tflt	Lebo and Tullock members of the Fort Union Formation

MESOZOIC

Cretaceous

Kl	Lance Formation
Klm	Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Bearpaw and Lewis shales
Kfh	Fox Hills Sandstone
Kfl	Fox Hills Sandstone and Lewis Shale
Kfb	Fox Hills Sandstone and Bearpaw Shale
Kml	Meeteetse Formation and Lewis Shale
Kmv	Mesaverde Group
Kc	Cody Shale
Kf	Frontier Formation
Kft	Frontier Formation and Mowry and Thermopolis shales
Kp	Pierre Shale
Kn	Niobrara Formation
Knc	Niobrara Formation and Carlile Shale
Kcl	Carlile Shale
Kgb	Greenhorn Formation and Belle Fourche Shale
Kgbm	Greenhorn Formation and Belle Fourche and Mowry shales
Kmr	Mowry Shale
Kmt	Mowry and Thermopolis shales
Kns	Newcastle Sandstone and Skull Creek Shale

Cretaceous-Jurassic

KJ	Cloverly and Morrison formations (W/SW) or Inyan Kara Group and Morrison Formation (E/SE)
KJs	Cloverly, Morrison, and Sundance formations
KJg	Cloverly, Morrison, Sundance, and Gypsum Spring formations

Jurassic

Jsg	Sundance and Gypsum Spring formations

Triassic

TRcd	Chugwater and Dinwoody formations
TRc	Chugwater Formation

MESOZOIC AND PALEOZOIC

Triassic-Permian

TRPcg	Chugwater and Goose Egg formations
TRPs	Spearfish Formation
TRPg	Goose Egg Formation

PALEOZOIC

Pzr	Paleozoic units, undifferentiated

Permian

Pp	Phosphoria Formation and related rocks
Pmo	Minnekahta Limestone and Opeche Shale

Permian-Pennsylvanian

PIPh	Hartville Formation
PIPm	Minnelusa Formation

Permian-Mississippian

PM	Tensleep Sandstone and Amsden Formation

Mississippian

Mm	Madison Limestone or Group

Mississippian-Devonian

MD	Madison Limestone or Darby Formation
MDg	Guernsey Formation
MDe	Pahasapa and Englewood limestones

Mississippian-Ordovician

MO	Madison Limestone and Bighorn Dolomite

Ordovician-Cambrian

OꞒ	Whitewood Dolomite, and Winnipeg and Deadwood formations (E), or Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone (W)

Ordovician

Ob	Bighorn Dolomite

Cambrian

Ꞓr	Cambrian rocks

PRECAMBRIAN

Proterozoic

Xsv	Pelitic schist, marble, granite gneiss, layered amphibolite, and felsic gneiss

Archean

Wmu	Amphibolite
Wg	Granite and minor amounts of metasedimentary rocks
WVsv	Amphibolite, hornblende gneiss, biotite gneiss, quartzite, iron-formation, metaconglomerate, marble, and pelitic schist
WVg	Quartz diorite to quartz monzonite
Ugn	Oldest gneiss complex

Montana Geologic Units

CENOZOIC

Quaternary

Qal	Alluvium

Tertiary

Tw	Wasatch Formation
Tfu	Fort Union Formation

MESOZOIC

Cretaceous

Khc	Hell Creek Formation
Kfh	Fox Hills Sandstone
Kp	Pierre Shale
Kfb	Fox Hills Sandstone and Bearpaw Shale
Kjr	Judith River Formation
Kn	Niobrara Formation
Kce	Carlile Shale
Kg	Greenhorn Formation
Kbf	Belle Fourche Shale
Kmo	Mowry Formation

Triassic

TRu	Triassic units, undifferentiated

Montana Geologic Units (continued)

PALEOZOIC (continued)

Pennsylvanian

PNu	Pennsylvanian units, undifferentiated

Mississippian-Devonian

Mu	Mississippian units, undifferentiated

Ordovician

Ou	Ordovician units, undifferentiated

Nebraska Geologic Units

CENOZOIC

Tertiary

Ta	Arikaree Group
Tw	White River Group

MESOZOIC

Cretaceous

Kp	Pierre Shale

South Dakota Geologic Units

CENOZOIC

Quaternary

Qal	Alluvium
Qt	Terrace deposits
Ql	Landslide deposits

Tertiary

Tt	Trachytic intrusive rocks

MESOZOIC

Cretaceous

Kp	Pierre Shale
Kn	Niobrara Formation
Kg	Greenhorn Formation
Kb	Belle Fourche Shale
Kms	Mowry Shale, Newcastle Sandstone, and Skull Creek Shale
Kfl	Inyan Kara Group

Jurassic

Jms	Morrison Formation, Unkpapa Sandstone, Sundance Formation, and Gypsum Spring Formation

MESOZOIC AND PALEOZOIC

Triassic-Permian

TRPs	Spearfish Formation

PALEOZOIC

Permian

Pmo	Minnekahta Limestone and Opeche Shale

Permian-Pennsylvanian

PIPm	Minnelusa Formation

Mississippian-Devonian

MDpe	Madison Group

Ordovician-Cambrian

OꞒwd	Whitewood Limestone, and Winnipeg and Deadwood formations

PRECAMBRIAN

Proterozoic

XWp	Pegmatite
XWb	Metabasalt
XWgw	Metagraywacke

Map Projection: Universal Transverse Mercator (UTM), zone 13
False Easting: 500000, False Northing: 0
Central Meridian: -106.0 degrees West
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)

Map layout by James R. Rodgers and James E. Stafford
Map edited by Suzanne C. Luhr

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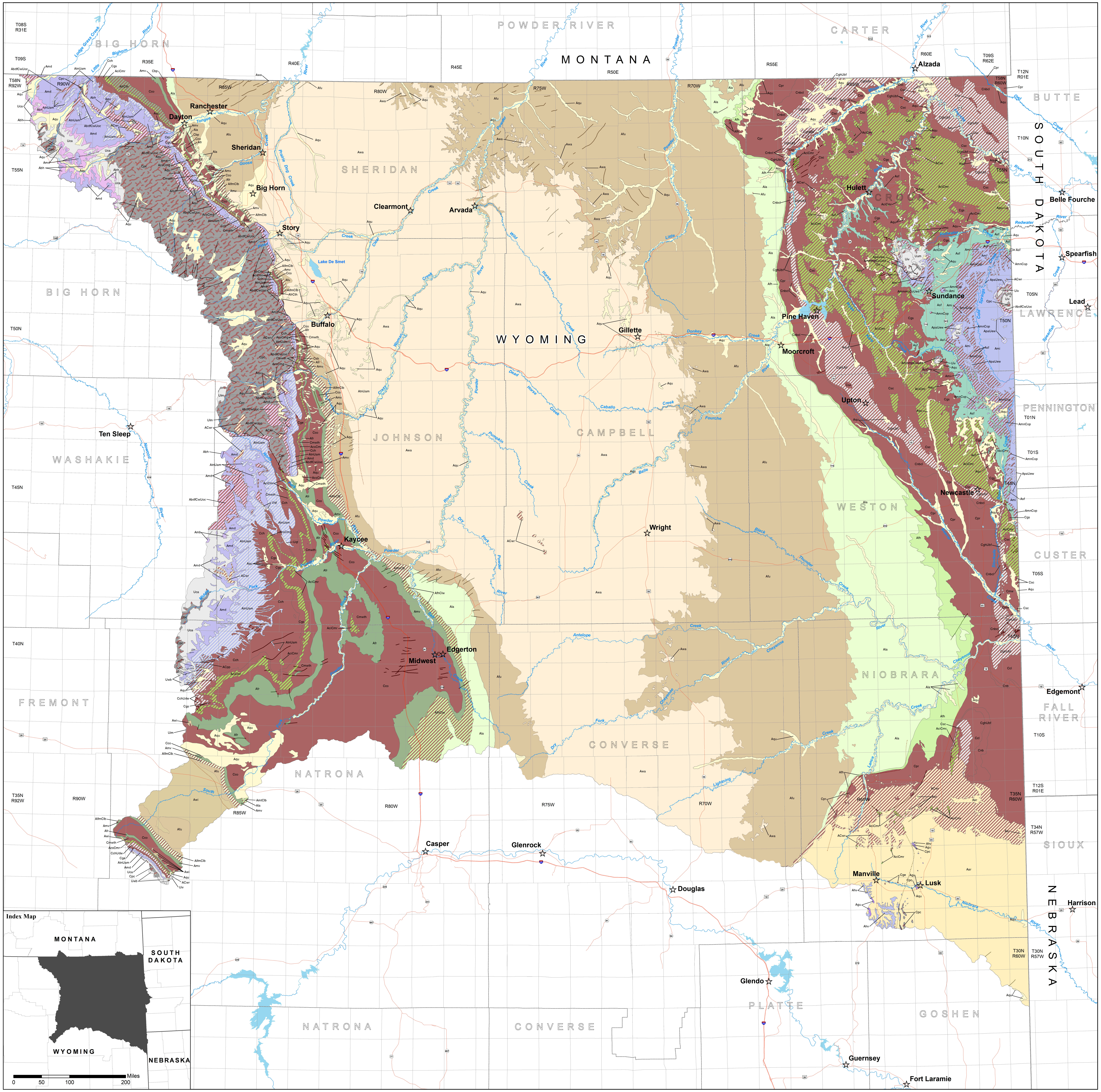

Hydrogeology - Powder, Tongue, and Northeast River Basins
Wyoming

compiled by
Timothy T. Bartos and James E. Stafford

Magnetic Declination = 9.03° E
at center of map
(November 5, 2019)

0 5 10 15 20 25 30 Miles

Scale 1:400,000

Explanation

Interstate highway
U.S. highway
State highway
☆ City or town
Township boundary
County boundary
State boundary
Lake or reservoir
River or creek
Normal fault—dotted where concealed
Thrust fault—dotted where concealed

Hydrogeology

Hydrogeologic Units - Compiled from Figures 7-2 and 7-8

CENOZOIC

Quaternary

Aqu	Quaternary unconsolidated-deposit aquifer

Quaternary-Tertiary

Uqt	undefined Quaternary-Tertiary glacial deposits

Tertiary

Uum	undefined Upper Miocene
Ulm	undefined Lower Miocene
Aar	Arikaree aquifer
Umo	undefined Lower Miocene and Upper Oligocene
ACwr	White River aquifer and confining unit
Uwb	undefined Wagon Bed
Uiv	undefined igneous volcanic
Awi	Wind River aquifer
Awa	Wasatch aquifer
Uim	undefined Indian Meadows
Afu	Fort Union aquifer

MESOZOIC

Cretaceous

Ala	Lance aquifer
AlfmClb	Lance, Fox Hills, and Meeteetse aquifers, Lewis and Bearpaw confining units
Afh	Fox Hills aquifer
Cbp	Bearpaw confining unit
AfhClw	Fox Hills aquifer and Lewis confining unit
AmtClb	Meeteetse aquifer, and Lewis and Bearpaw confining units
Cpr	Pierre confining unit
Amv	Mesaverde aquifer
Cco	Cody confining unit
Cnb	Niobrara confining unit
Cnbcl	Niobrara and Carlile confining units
Ccl	Carlile confining unit
Afr	Frontier aquifer
AfrCth	Frontier aquifer and Thermopolis confining unit
CghUbf	Greenhorn confining unit and undefined Belle Fourche
Cmw	Mowry confining unit
Cmwth	Mowry and Thermopolis confining units
Csc	Skull Creek confining unit

Cretaceous-Jurassic

AciCmr	Cloverly and Inyan Kara aquifers, and Morrison confining unit
AcsCmg	Cloverly and Sundance aquifers, and Morrison and Gypsum Spring confining units
AcsCmr	Cloverly and Sundance aquifers, and Morrison confining unit

MESOZOIC (continued)

Jurassic

Cgs	Gypsum Spring confining unit

Triassic

CchUdw	Chugwater confining unit and undefined Dinwoody
Cch	Chugwater confining unit

MESOZOIC AND PALEOZOIC

Triassic-Permian

Asf	Spearfish aquifer
Cge	Goose Egg confining unit

PALEOZOIC

Undivided

AmmmpCoUed	Minnekahta, Minnelusa, Madison, and Pahasapa aquifers, Opeche confining unit, and undefined Englewood and Darby

Permian

ACpp	Phosphoria aquifer and confining unit
AmnCop	Minnekahta aquifer and Opeche confining unit

Permian-Pennsylvanian

Ahv	Hartville aquifer
Ami	Minnelusa aquifer

Permian-Mississippian

AtnUam	Tensleep aquifer and undefined Amsden

Mississippian-Devonian

Amd	Madison aquifer
Agu	Guernsey aquifer
ApaUew	Pahasapa aquifer and undefined Englewood

Mississippian-Ordovician

Amb	Madison and Bighorn aquifers

Ordovician-Cambrian

AbdfCwUoc	Bighorn, Deadwood, and Flathead aquifers, Winnipeg confining unit, and undefined Ordovician/Cambrian

Ordovician

Abh	Bighorn aquifer

Cambrian

Uca	undifferentiated Cambrian

PRECAMBRIAN

Cpc	Precambrian basal confining unit

Map Projection: Universal Transverse Mercator (UTM), zone 12
False Easting: 500000, False Northing: 0
Central Meridian: -106.0 degrees West
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)

Map layout by James E. Stafford
Map editied by Suzanne C. Luhr

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Geographic region	Spring discharge		Well yield								Specific capacity		Transmissivity														Hydraulic conductivity		Storativity/storage coefficient		Permeability				Porosity		Sources
	Flowing		Flowing		Pumped or unknown		Wells associated with oil/gas exploration and development		All wells (pumped or flowing)				Flow test		Constant rate test		Recovery		Observation well		Drill stem or other oil/gas exploration and development field test		Unspecified/other		All tests		Wells associated with oil/gas exploration and development				Wells associated with oil/gas exploration and development		All other data		Wells associated with oil/gas exploration and development		
	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)/ft]	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft^2/day)	Count	Range (ft/day)	Count	Range (unitless)	Count	Range (md)	Count	Range (md)	Count	Range (percent)	
Cenozoic hydrogeologic units																																					
Quaternary alluvial aquifers																																					
NERB			1	2	109	1–1,000 (15)			110	1–1,000 (15)	59	0.11–62 (3.0)					1	1,300					13	28.1–10,700	14	28.1–10,700							7	770–60,000			1, 30, 52, 62–64, 74
Quaternary terrace-deposit aquifers																																					
NERB	1	320			10	4.1–25 (12.5)			10	4.1–25 (12.5)	5	1–20 (3.1)											2	938; 2,410													1, 30, 52, 74
Quaternary dune sand (eolian) deposits																																					
NERB					2	2.75; 5			2	2.75; 5																											1, 8
Quaternary landslide deposits																																					
NERB	1	50																																			30
Quaternary glacial deposits																																					
NERB	1	395																																			1, 63
Arikaree aquifer																																					
NERB			2	1; 150	156	0.3–2,000 (500)			158	0.3–2,000 (500)	78	0.13–230 (8.2)			3	80–8,890	4	56–17,800	2	3,300; 15,900			6	1,070–11,300	15	56–17,800	2	1.2; 1.3	3	0.001–0.006			4	1,600–17,000			1, 3, 12, 40, 54, 62, 73
White River hydrogeologic unit																																					
NERB					10	3–6 (5)			10	3–6 (5)	7	0.03–3 (0.17)																									1, 62
Wind River aquifer																																					
WRSB	1	5	2	1.25; 1.25	4	5–20 (6.5)			6	1.25–20 (5)	1	3.3																									1, 16
Wasatch aquifer																																					
NERB	9	0.06–12 (2)	95	0.25–80 (3)	453	0.1–1,470 (7)			548	0.1–1,470 (7)	290	0.004–350 (0.19)			1	10.7	4	5.4–295	1	8.7					6	5.4–295			1	0.00006							1, 17, 21, 28–30, 52, 59, 63, 74
Coal aquifers					4	3–15 (11)			4	3–15 (11)	3	0.11–0.28 (0.17)											1	69.7	1	69.7			1	0.02			1	360			1, 30
Fort Union aquifer																																					
NERB	5	4–200 (9)	160	0.25–60 (5.75)	432	0.5–1,500 (15)			592	0.25–1,500 (10)	230	0.003–2,200 (0.39)			32	12.7–1,330	38	1.3–474	10	73.7–470			10	4.02–236	90	1.3–1,330	2	0.37; 0.39	18	0.00001–0.008			7	27–430			1–2, 13, 17–23, 28–30, 32, 35, 38, 43–45, 47–50, 52, 59, 62–65, 74
Coal aquifers			3	0.71–5 (2)	12	0.5–111 (5)			15	0.5–111 (5)	2	0.004; 0.03																									30
WRSB					1	15			1	15																											1
Mesozoic hydrogeologic units																																					
Lance aquifer																																					
NERB	1	5	4	1.2–5 (2.7)	190	0.75–300 (10)			194	0.75–300 (10)	54	0.01–1.8 (0.24)			4	16.2–40.2	3	13.5–80.4	1	17			7	22.8–281	15	13.5–281			2	0.0001; 0.03			3	330–1,900			1, 17, 21, 30, 33, 52, 55, 57, 62–64, 74
Fox Hills aquifer																																					
NERB					46	2–5,000 (10)			46	2–5,000 (10)	23	0.03–4.9 (0.25)					2	214; 324					1	214	3	214–324							1	1,900			1, 4, 16, 21, 29, 33, 44, 62, 64
Lewis confining unit																																					
NERB					1	6			1	6																											30
Pierre confining unit																																					
NERB					7	2–60 (8)			7	2–60 (8)	4	0.14–1.3 (0.36)																									1, 62, 64
Mesaverde aquifer																																					
NERB			1	0.5	20	2–130 (8)	5	12.5–34 (24)	26	0.5–130 (11)	8	0.06–1.4 (0.17)									8*	0–47.8	1	201	9*	0–201					9*	0–230			5*	15–21	1, 15–17, 21, 30, 51–52, 63, 67–68, 74
Cody confining unit																																					
NERB			2	0.25; 6	13	1.5–15 (5)	2	1; 19	17	0.25–19 (5)	5	0.02–1.4 (0.1)									5	0.05–15.7			5	0.05–15.7					5	2–280			5	12–25	1, 15–17, 21, 51–52, 63, 68, 74
Steele confining unit																																					
NERB							8	10–40 (20.8)	8	10–40 (20.8)											7	9.8–295			7	9.8–295					7	11–330					51
Frontier aquifer																																					
NERB			25	0.08–5 (2)	18	0.28–16 (5)	2	7 (flowing); 7 (pumping)	45	0.08–16 (3)	5	0.02–0.64 (0.11)									15*	0.03–18.9			15*	0.03–18.9					9	0.5–520			10	12–21	1, 8, 15–16, 21, 30, 52, 63, 67, 74
Mowry confining unit																																					
NERB	1	3	2	0.25; 2	6	0.28–40 (17)			8	0.25–40 (8)																											1, 16, 28, 52
Muddy aquifer																																					
NERB			1	45	1	10	1	0.5	3	0.5–45 (10)											13*	0.1–19.6			13*	0.1–19.6					18*	2.4–588			21*	2–22	1, 15–16, 21, 51–52, 67, 69–71, 74
WRSB					1	10			1	10																											1
Newcastle aquifer																																					
NERB					1	25			1	25											12*	0.01–8.3			12*	0.01–8.3					13*	<1–330			10	9.3–23	1, 15, 21, 62, 67
Skull Creek confining unit																																					
NERB					1	0.3			1	0.3																											1
Cloverly aquifer																																					
NERB	1	<1	2	0.18; 25	5	0.08–18 (2)	2	1; 19	9	0.08–25 (2)	3	0.02–0.15 (0.02)									7*	0.5–31	2	26.8; 37.5	9*	0.5–37.5					8*	14–410			7	11–18	1, 8, 15–16, 21, 30, 52, 67–68
WRSB	1	5																																			1
Inyan Kara aquifer																																					
NERB	2	12; 104	47	0.2–150 (5)	60	1–300 (10)			107	0.2–300 (8)	25	0.01–3.1 (0.25)	2	29.5; 109	2	381; 1,510	1	208	1	441	8	4.8–29.2	5	38.1–2,120	19	4.8–2,120					9*	0–730	2	110; 770	8	14–24	1, 6, 14, 21, 53, 60, 62, 64, 66–67, 69, 71–72
Morrison confining unit																																					
NERB	1	31			3	3.5–6.2 (5)			3	3.5–6.2 (5)	2	0.2; 0.26											2	21.4; 21.4	2	21.4; 21.4							2	220; 270			1, 64
Sundance aquifer																																					
NERB	6	1–50 (6.5)	3	0.5–5 (2)	9	1.5–40 (8)	1	13	13	0.5–40 (5)	3	0.02–0.06 (0.04)									3	0.02–52.8			3	0.02-52.8					3	<1–440			3	12–21	1, 14–16, 21, 52, 64, 67–68
Chugwater confining unit																																					
NERB	2	5; 120			1	8			1	8																											1, 16, 52, 74
Spearfish aquifer																																					
NERB	1	1			12	2–10 (6)			12	2–10 (6)	3	0.26–0.61 (0.54)											2	20; 50	2	20; 50							2	330; 440			1, 64
Paleozoic and Precambrian hydrogeologic units																																					
Minnekahta aquifer																																					
NERB			1	12	2	3; 25			3	3; 25 (12)																							1	240			1, 11
Tensleep aquifer																																					
NERB			6	9–2,620 (125)	11	5–1,200 (22)	2	32; 54	19	5–2,620 (33)	2	0.33; 10									12*	0.003–255			12*	0.003–255					9*	0.01–700			8*	0.4–20	1, 15–17, 21, 24, 28, 34, 51–52, 63, 67–68, 74
WRSB			1	20					1	20																											16
Amsden hydrogeologic unit																																					
NERB	1	1	1	0.5					1	0.5																							1	24			11, 34, 52
Minnelusa aquifer																																					
NERB	1	15	13	5–375 (41)	32	1.5–301 (13.5)			45	1.5–375 (15)	19	0.1–38 (0.6)			1	1,620	2	1,580–3,800	1	2,130	6*	0.1–92			20*	0.1–3,800	2	6.5; 14	3	0.005–0.008	29*	0.5–>1,000			30*	5.8–25	1, 11, 15, 21, 41–42, 61, 64, 67–68, 71
Hartville aquifer																																					
NERB					1	104			1	104																											73
Madison aquifer																																					
NERB	2	200; 2,700	39	0.25–9,480 (200)	50	7.2–1,500 (265)	1	30	90	0.25–9,480 (238)	55	0.2–52 (1.6)	7	28.7–2,200	10	53.6–1,920	15	0.6–5,000			1	4.3	8	6.7–40,200	41	0.6–40,200	1	2.1	1	0.0002			4	2.2–120,000			1, 5–7, 9–11, 14, 16, 21, 24–27, 31, 36–37, 39, 41, 44, 46, 51–52, 56, 58, 61, 74
Bighorn aquifer																																					
NERB							1	28	1	28											1	5.1			1	5.1					1	5.5					51
Whitewood aquifer																																					
NERB																																	1	35,000			11
Flathead aquifer																																					
NERB	1	10	1	55	2	15; 20			3	15–55 (20)	2	0.57; 0.75																									1, 11, 30
Precambrian basal confining unit																																					
NERB	15	0.3–11 (2)			1	12			1	12	1	12																									1, 30, 63

[NERB, Northeastern River Basins study area excluding Wind River structural basin; WRSB, Wind River structural basin; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot of drawdown; ft^2/day, feet squared per day; ft/day, feet per day; md, millidarcy. *Values reported as range or average in original source so count cannot be determined.]

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Plate 3. Summaries of spring discharge, well yield, and hydraulic properties, Northeastern River Basins study area, Wyoming.

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