Chapter 7

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

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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

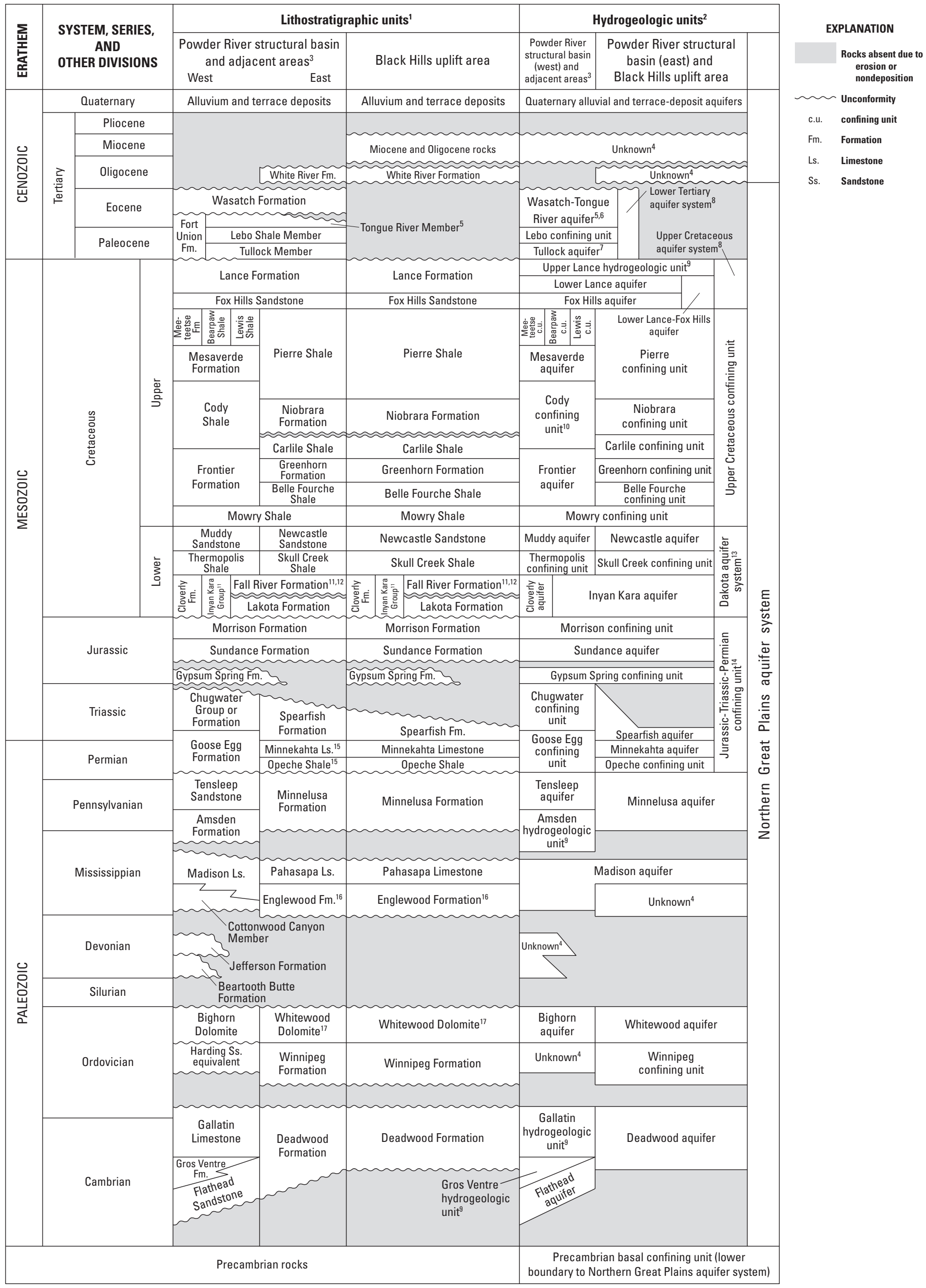
Saturated Quaternary unconsolidated deposits in the NERB study area include alluvium, terrace, dune sand (eolian), and glacial deposits (Hodson and others, 1973, sheet 3, and references therein; Feathers and others, 1981). Alluvium and terrace deposits consist of unconsolidated, poorly to well-sorted 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

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.

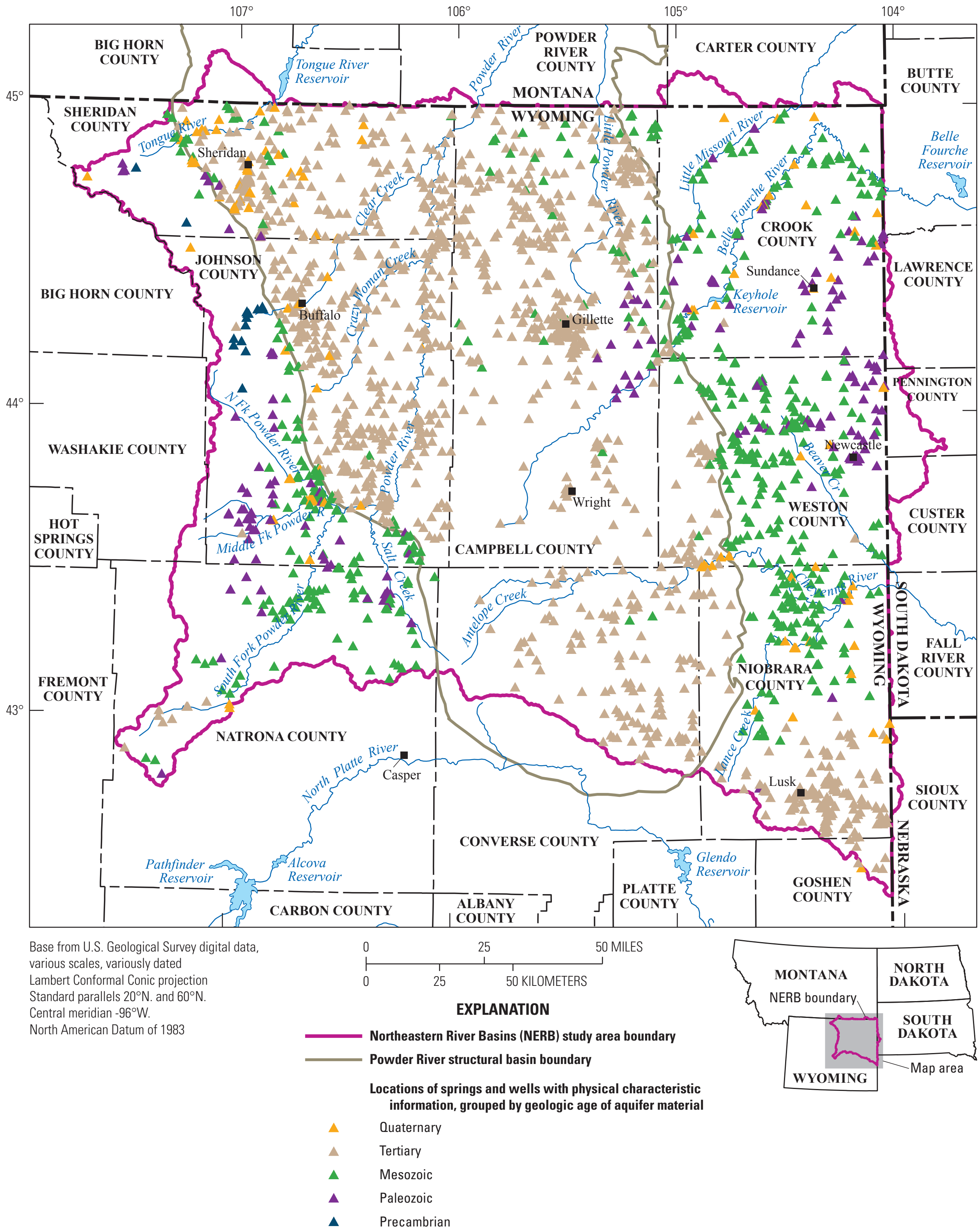


Figure 7-3. Locations of springs and wells with physical characteristic information, grouped by geologic age of aquifer material, Northeastern River Basins study area, Wyoming.

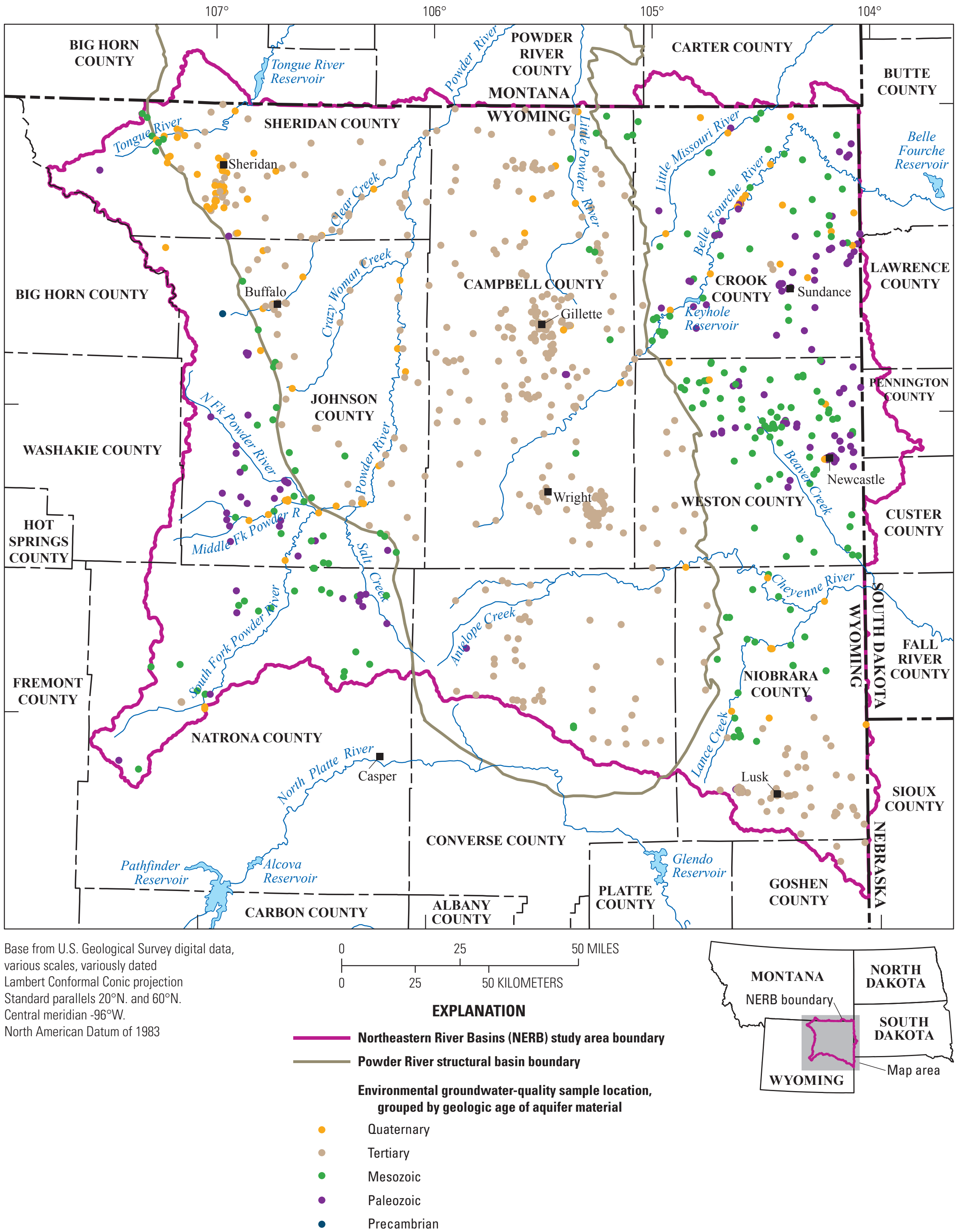


Figure 7-4. Environmental groundwater-quality sample locations, grouped by units of geologic age of aquifer material, Northeastern River Basins study area, Wyoming.

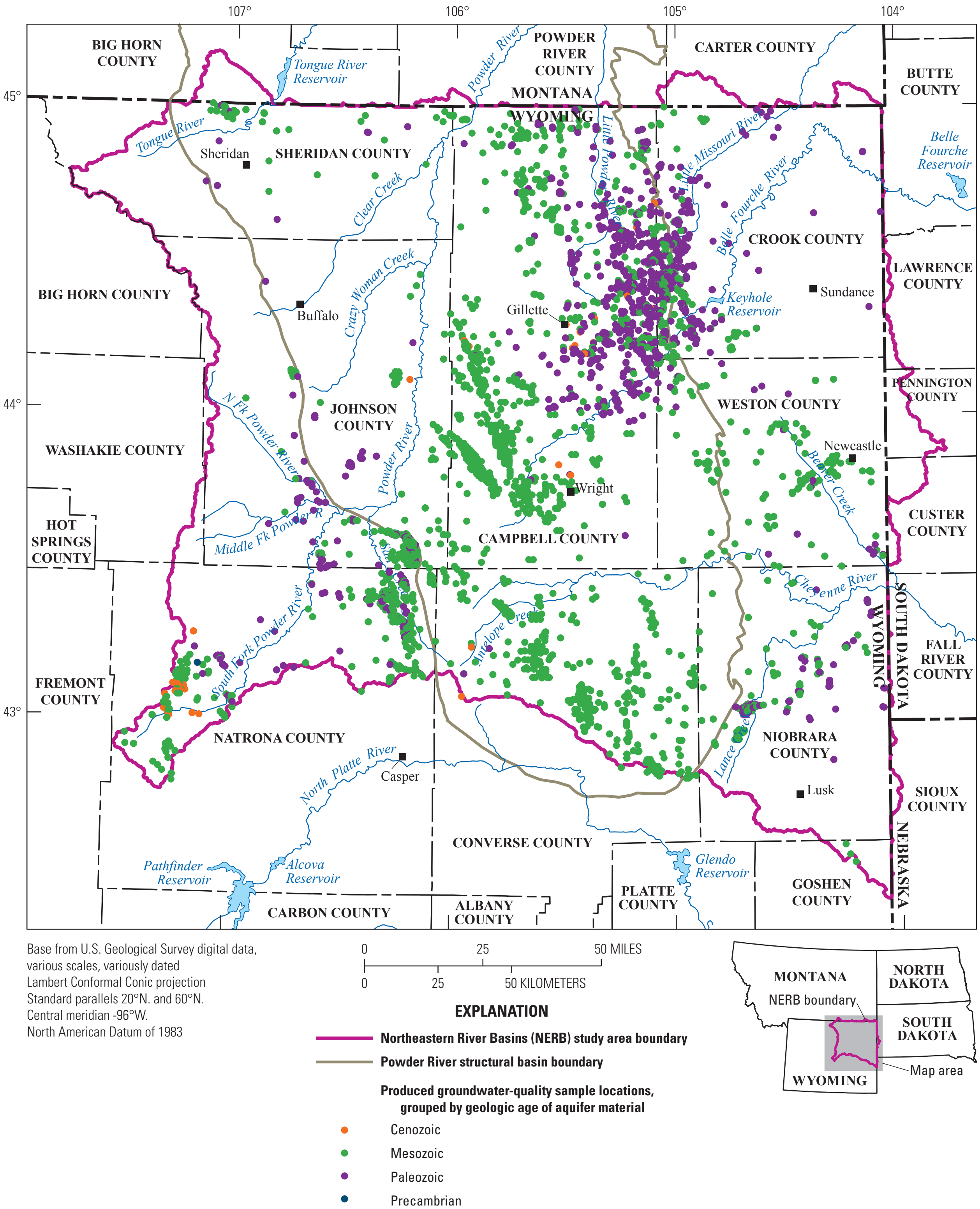


Figure 7-5. Produced groundwater-quality sample locations, grouped by geologic age of aquifer material, Northeastern River Basins study area, Wyoming.

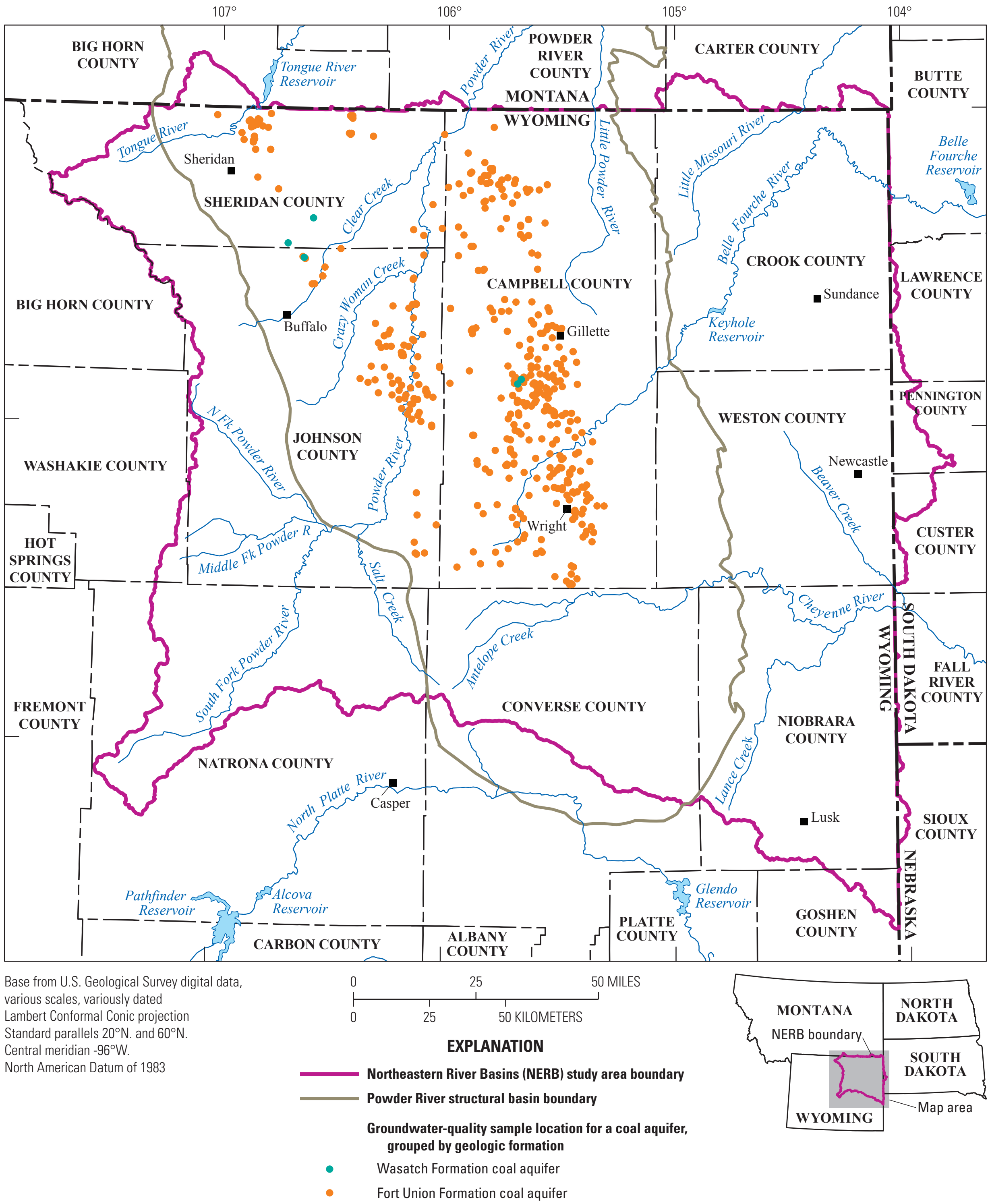


Figure 7-6. Coal aquifer groundwater-quality sample locations in the Powder River structural basin, grouped by geologic formation, Northeastern River Basins study area, Wyoming.

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

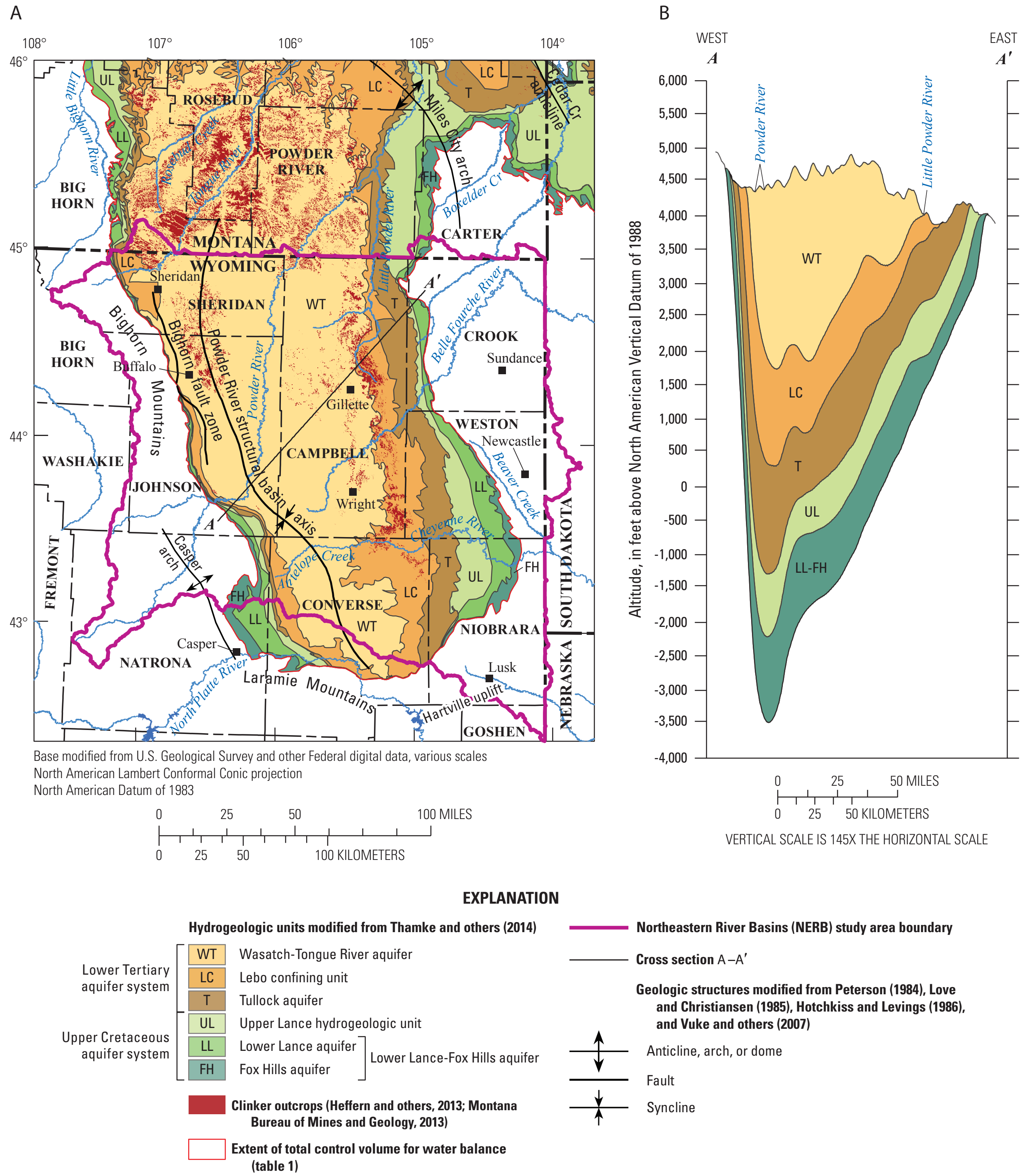


Figure 7-7. A, Outcrops of hydrogeologic units and B, cross section of the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana (modified from Thamke and others, 2014; and Long and others, 2014).

(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).

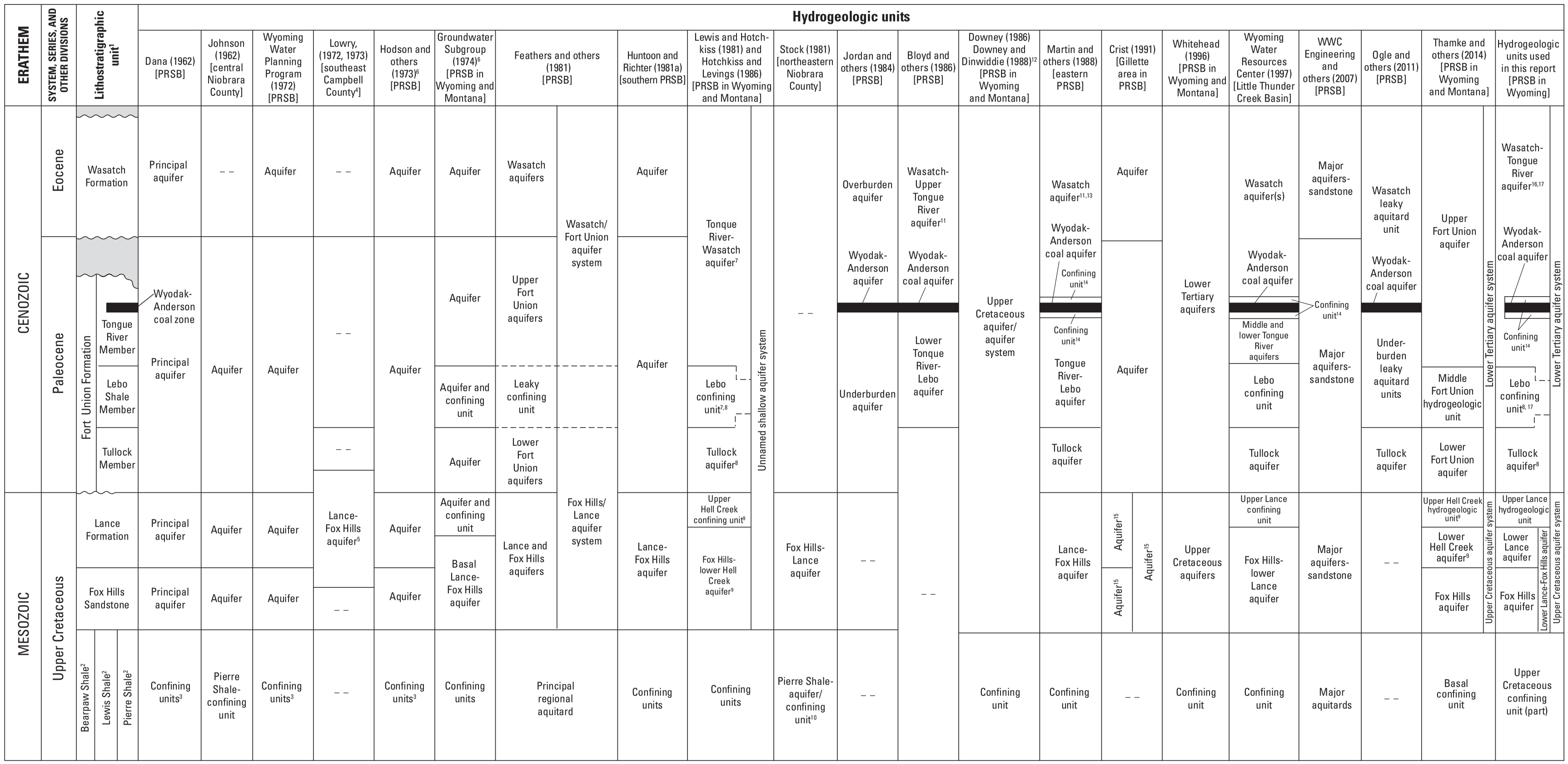
Induced leakage/hydraulic connection from some overlying sandstone aquifers in the Wasatch Formation and Tongue River Member of the Fort Union Formation to the Wyodak-Anderson coal aquifer has occurred in parts of the PRSB as a result of CBNG development (Ross and Zoback, 2008; Taboga and others, 2015, 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 (ft^3/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).

[ft^3/s, cubic feet per second; <, less than; --, not applicable]

Recharge or discharge component	Combined aquifer systems control volume[a]		Period of record
	ft^3/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.

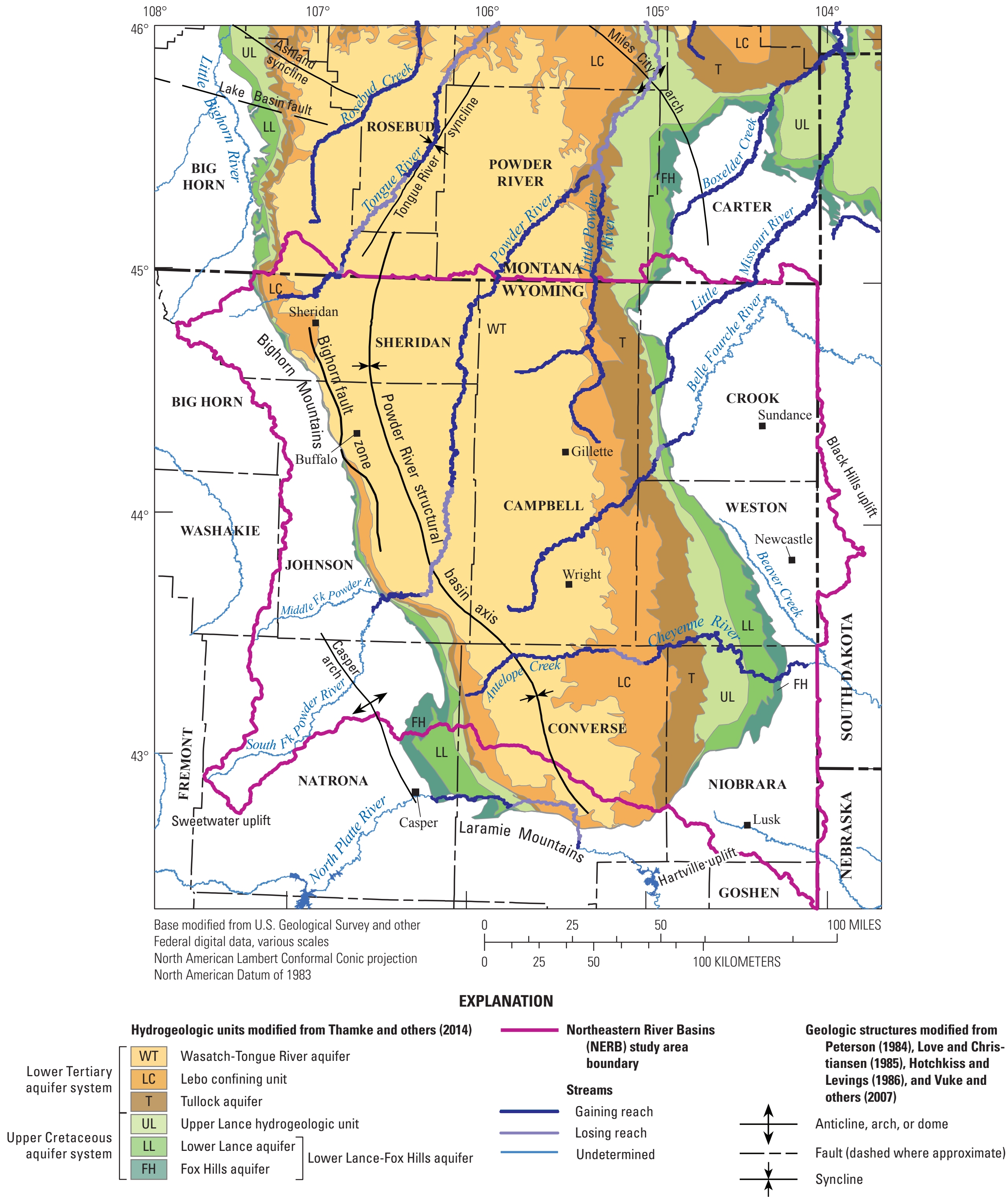


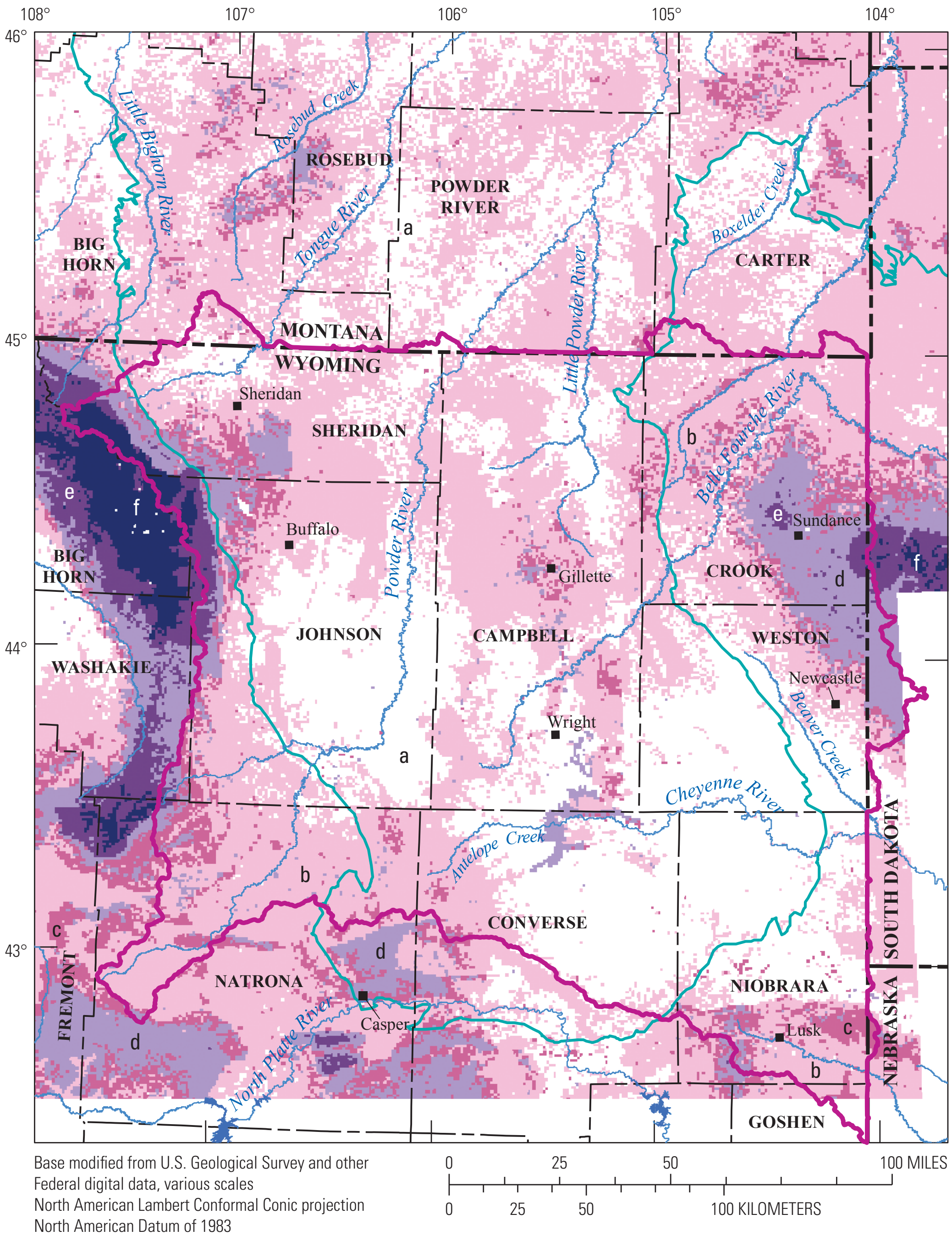
Figure 7-9. Gaining and losing stream reaches overlying the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin and adjacent areas, Northeastern River Basins study area, Wyoming and Montana (modified from Long and others, 2014).

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



EXPLANATION

Recharge, inches per year (1981–2005 average)

- a No recharge
- b >0 to 0.5
- c >0.5 to 1
- d >1 to 5
- e >5 to 10
- f >10 to 30

Northeastern River Basins (NERB) study area boundary

Extent of total control volume for combined lower Tertiary and Upper Cretaceous aquifer systems water balance, including recharge from precipitation (table 1)

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

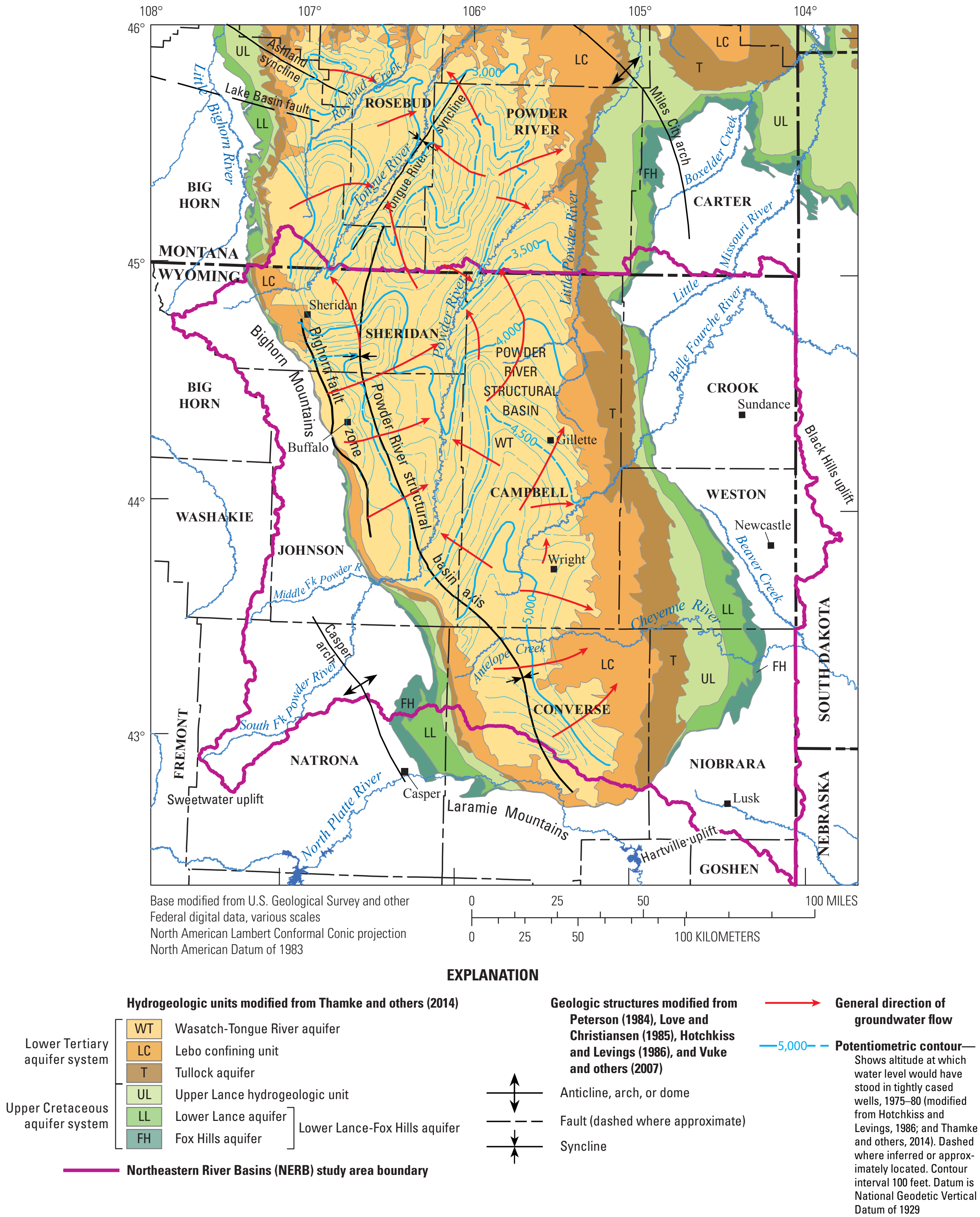


Figure 7-11. Potentiometric surface of the Wasatch-Tongue River aquifer in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

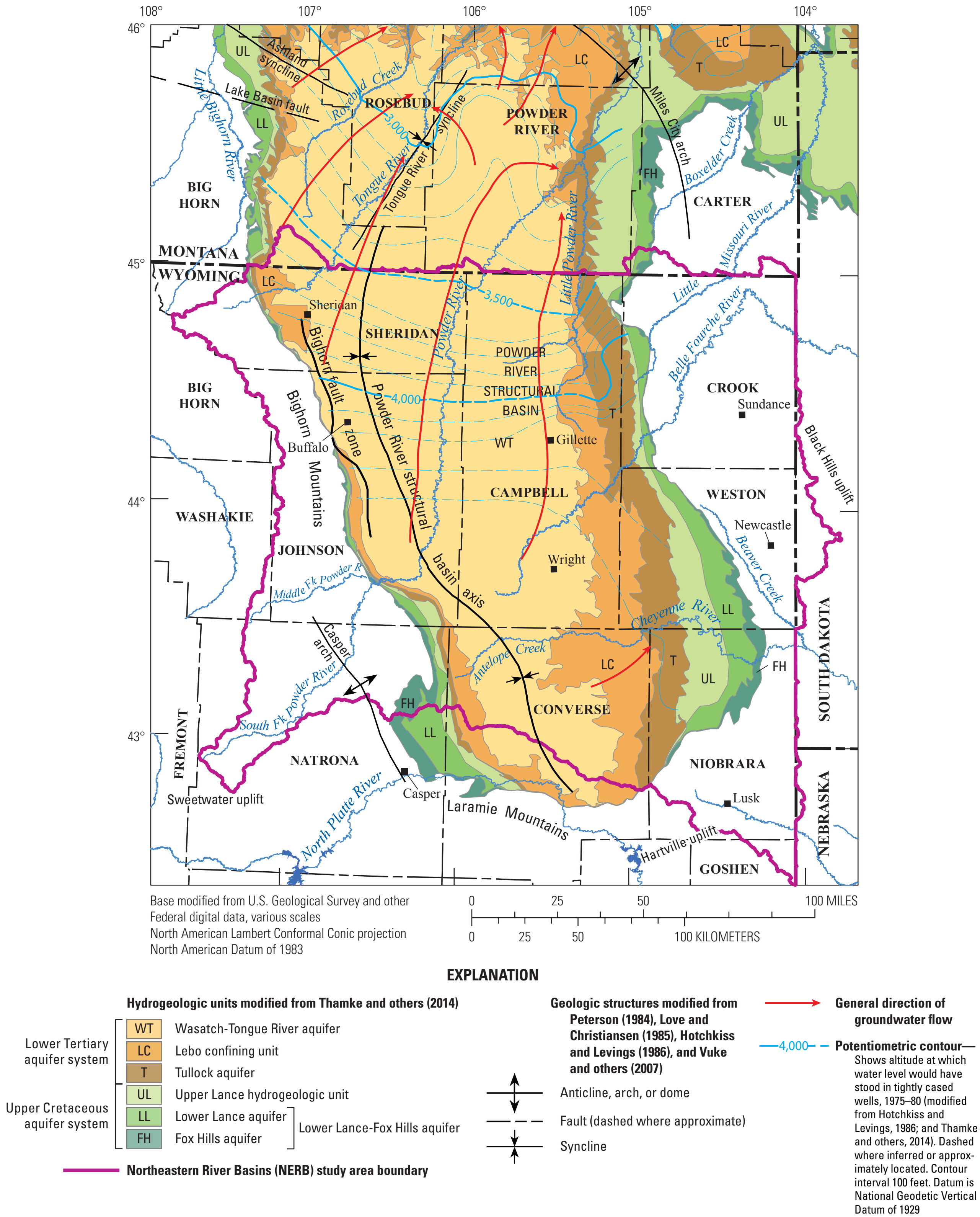


Figure 7-12. Potentiometric surface of the Tullock aquifer in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

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

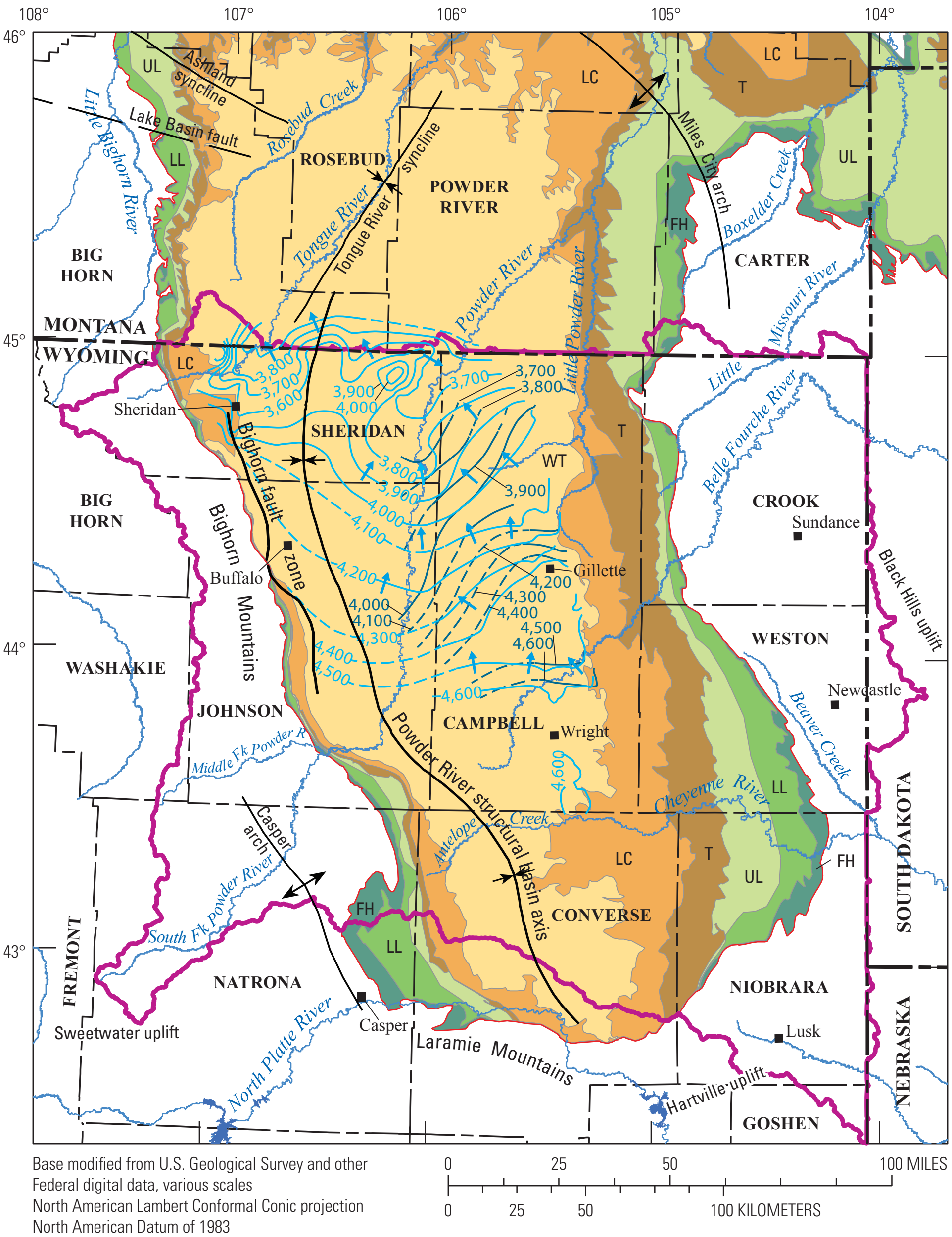
Long and others (2014) used both potentiometric-surface maps to calculate the difference in hydraulic head between the two aquifers. The calculated difference in hydraulic head ranged from -201 to 873 ft, with a mean of 311 ft (Long and others, 2014, table 6). The substantial difference in hydraulic 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



EXPLANATION

Hydrogeologic units modified from Thamke and others (2014)

Lower Tertiary aquifer system
- WT Wasatch-Tongue River aquifer
- LC Lebo confining unit
- T Tullock aquifer

Upper Cretaceous aquifer system
- UL Upper Lance hydrogeologic unit
- LL Lower Lance aquifer — Lower Lance-Fox Hills aquifer
- FH Fox Hills aquifer — Lower Lance-Fox Hills aquifer

Northeastern River Basins (NERB) study area boundary

Extent of total control volume for water balance, including recharge from precipitation (table 1)

General direction of groundwater flow

4,600 **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells (modified from Applied Hydrology, Inc., 2002). Datum is National Geodetic Vertical Datum of 1929. Dashed where inferred. Contour interval 100 feet.

4,600 **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells (modified from Daddow, 1986). Datum is National Geodetic Vertical Datum of 1929. Dashed where inferred. Contour interval 100 feet.

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 mi^2 (using 36-mi^2 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 ft^3/s) to both aquifer systems and about 71 percent (157.60 ft^3/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 ft^3/s) was estimated to be nearly equal to total recharge (222.86 ft^3/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-mi^2 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

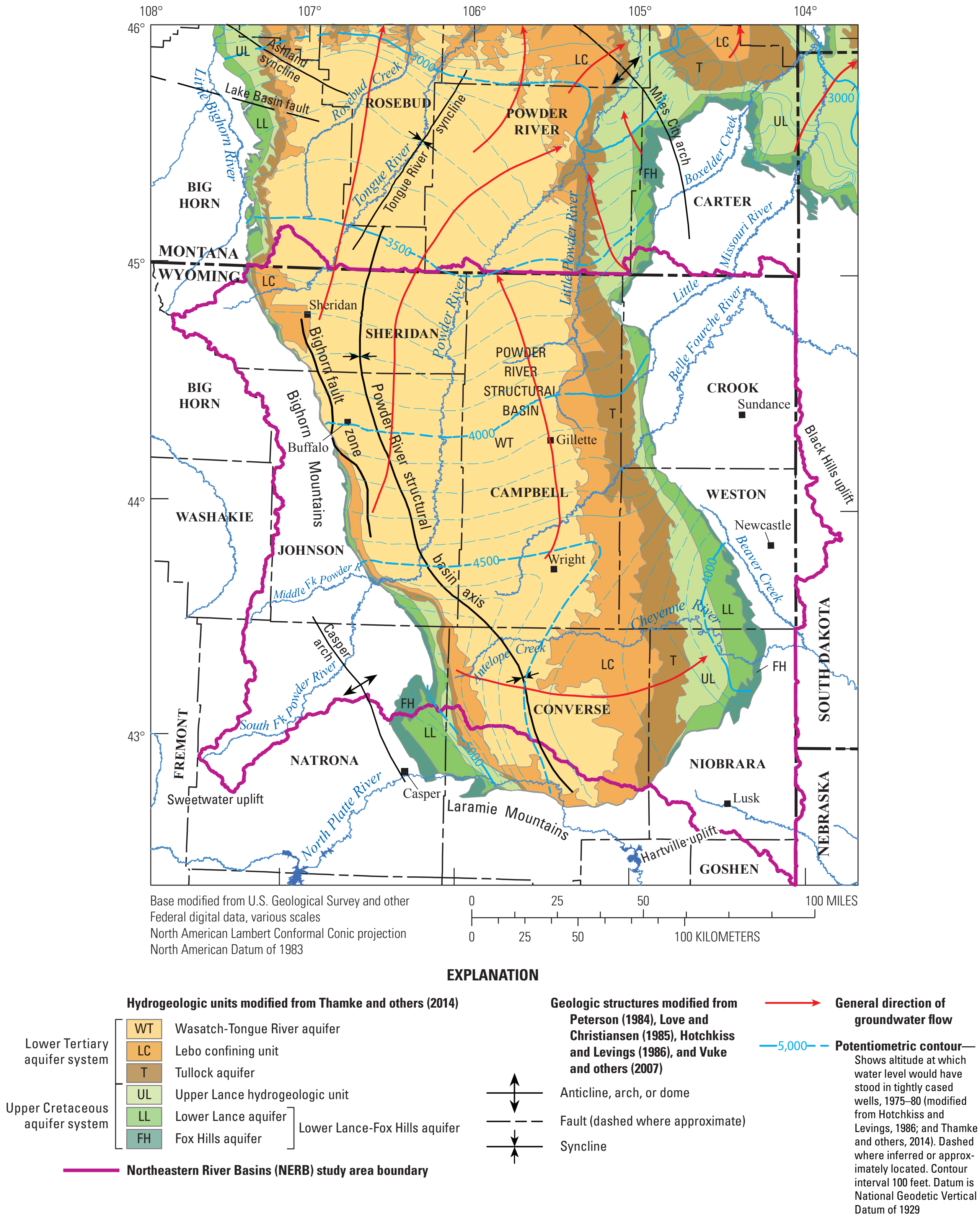


Figure 7-14. Potentiometric surface of the lower Lance-Fox Hills aquifer of the Upper Cretaceous aquifer system in the Powder River structural basin, Northeastern River Basins study area, Wyoming and Montana, 1975–80.

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-

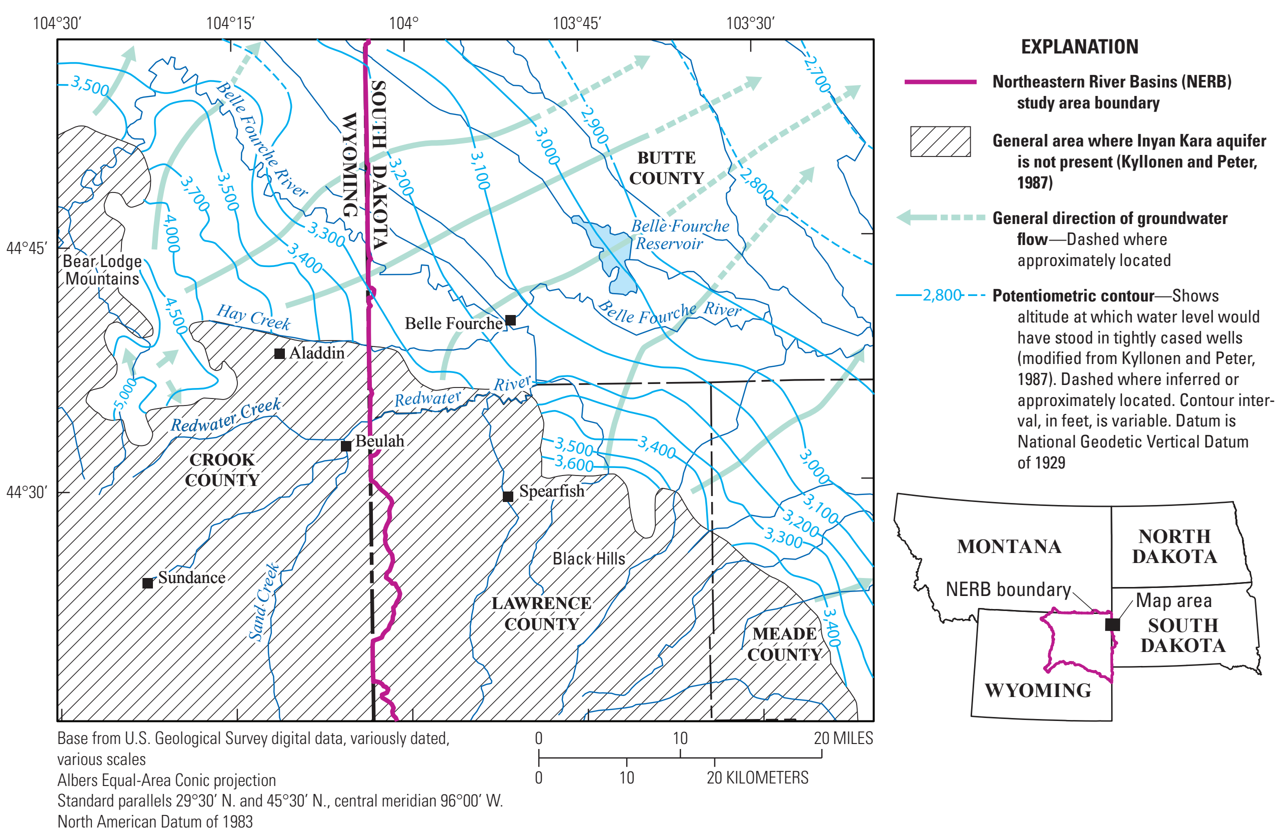


Figure 7-15. Potentiometric surface of the Inyan Kara aquifer in the northern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1960.

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 exceed 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.

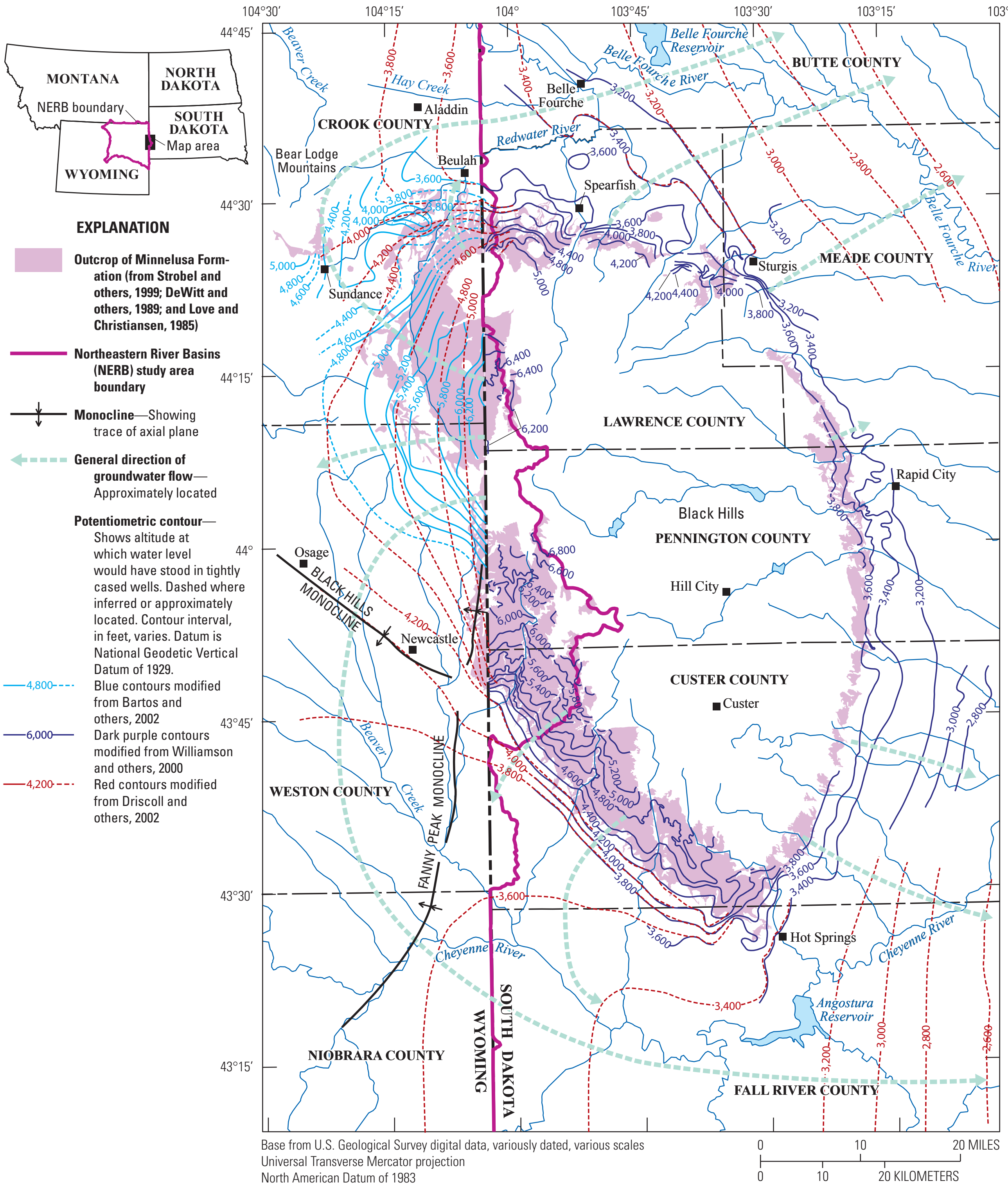


Figure 7-16. Potentiometric surfaces of the Minnelusa aquifer in the Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota.

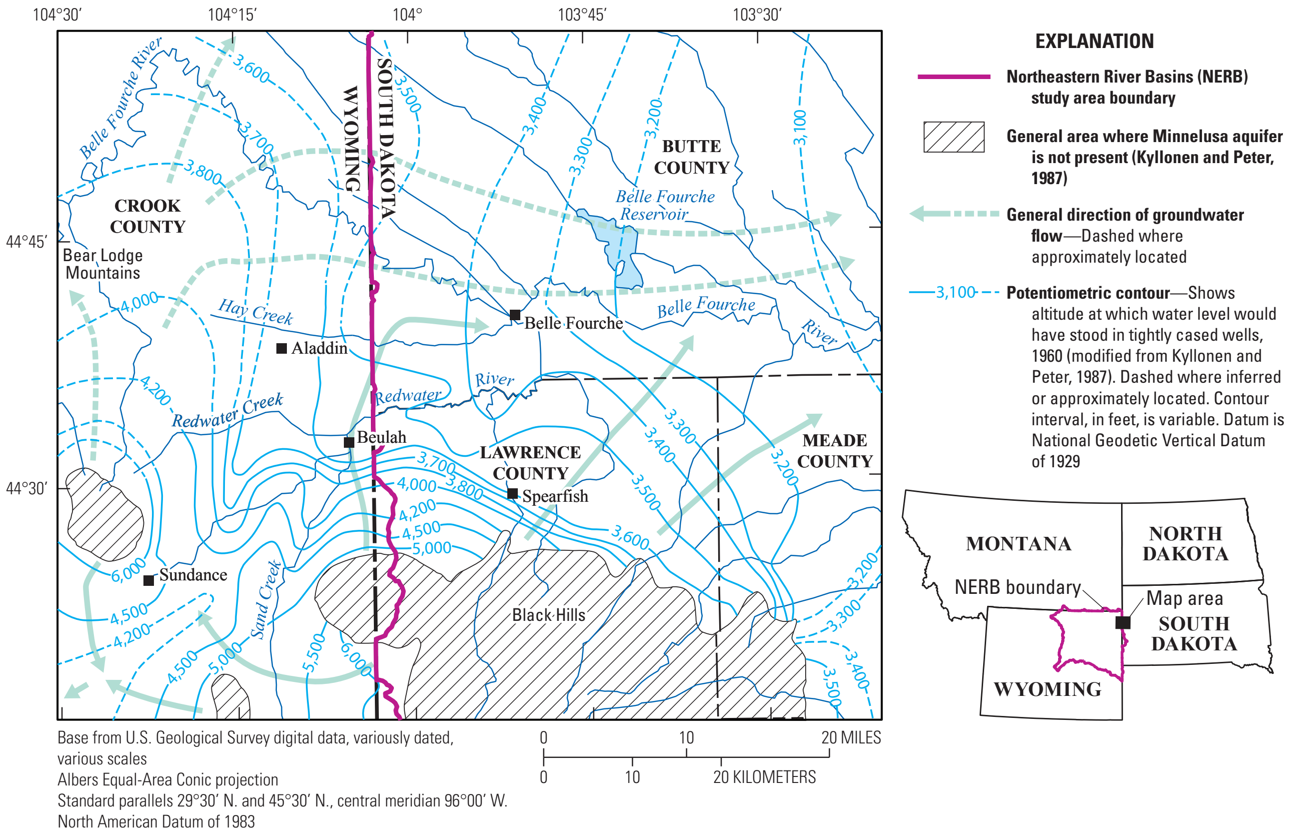


Figure 7-17. Potentiometric surface of the Minnelusa aquifer in the northwestern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1960.

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.

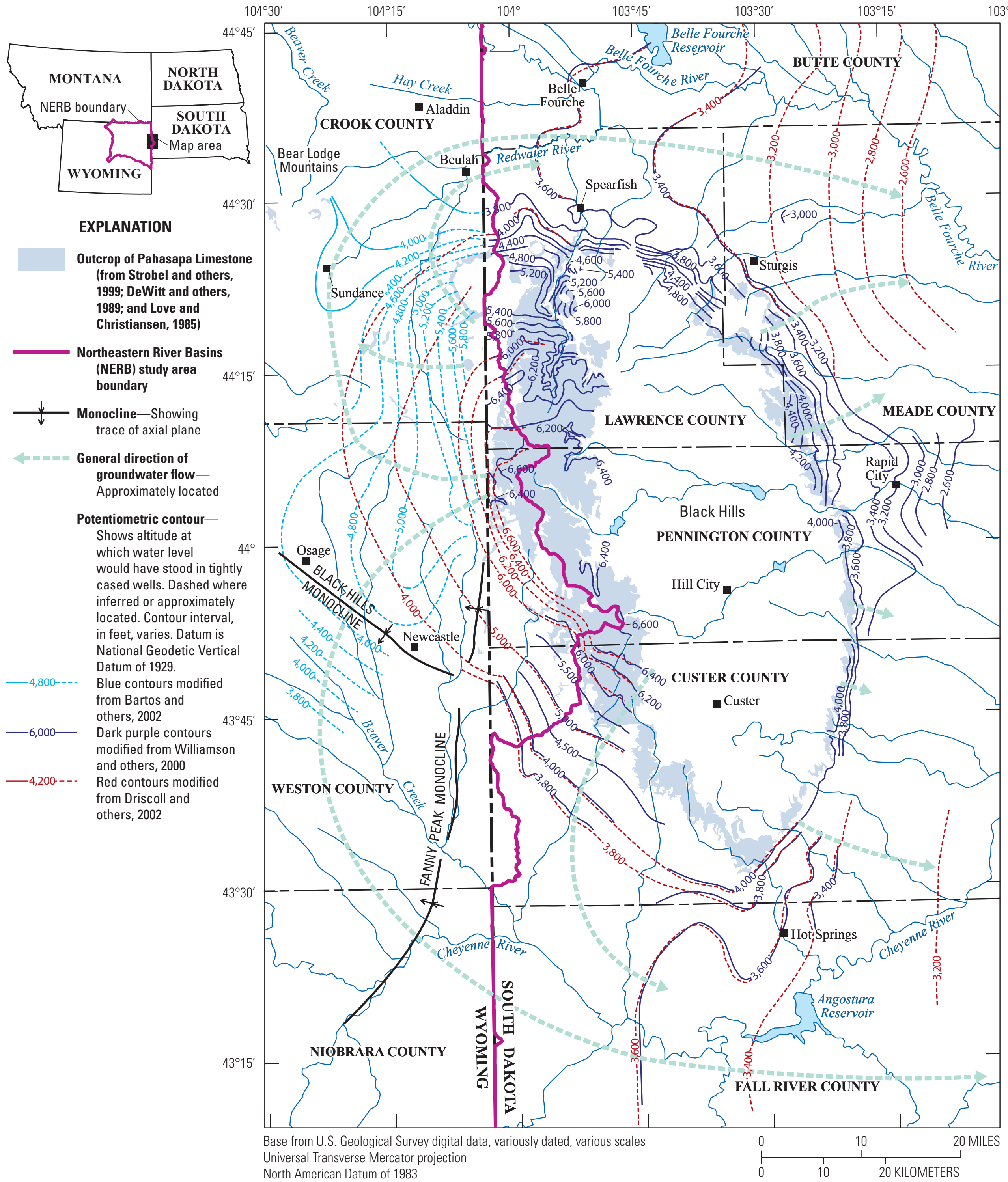


Figure 7-18. Potentiometric surfaces of the Madison aquifer in the Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota.

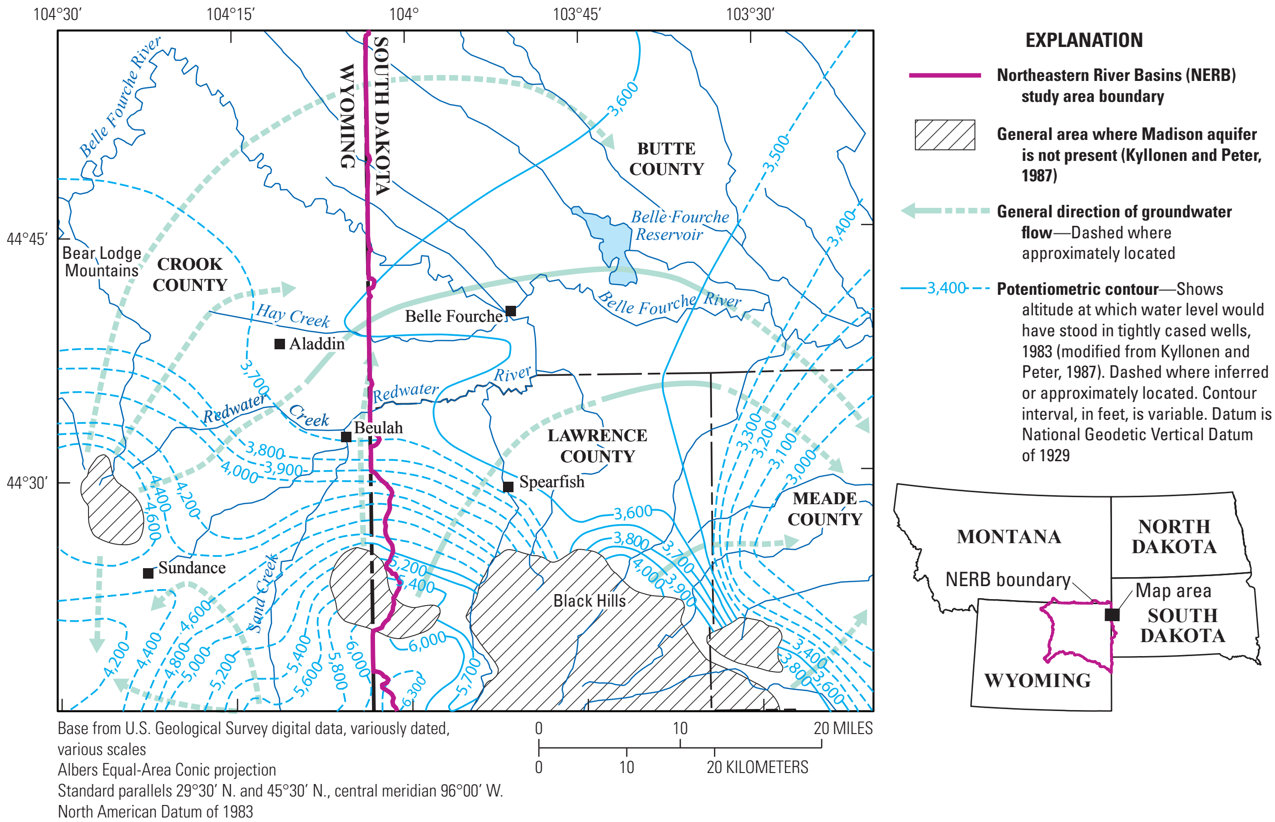


Figure 7-19. Potentiometric surface of the Madison aquifer in the northwestern Black Hills uplift area, Northeastern River Basins study area, Wyoming and South Dakota, 1983.

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 ft^3/sec of total inflows), and recharge from streamflow accounted for the remaining 27 percent of recharge (98 of 369 ft^3/sec of total inflows). Artesian springflow was the single largest outflow component and accounted for about 46 percent of total outflows (169 of 369 ft^3/sec) for the larger study area. Headwater springflow accounted for about 20 percent of the total outflows (72 of 369 ft^3/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 ft^3/sec). Well withdrawals accounted for about 8 percent of the total outflows for the larger study area (28 of 369 ft^3/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 ft^3/sec; fig. 7-20) is slightly smaller than for the study area consisting of only South Dakota (78 ft^3/sec) because measured average flows of about 6 ft^3/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). ft^3/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]	
	ft^3/s	Acre-feet	ft^3/s	Acre-feet	ft^3/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

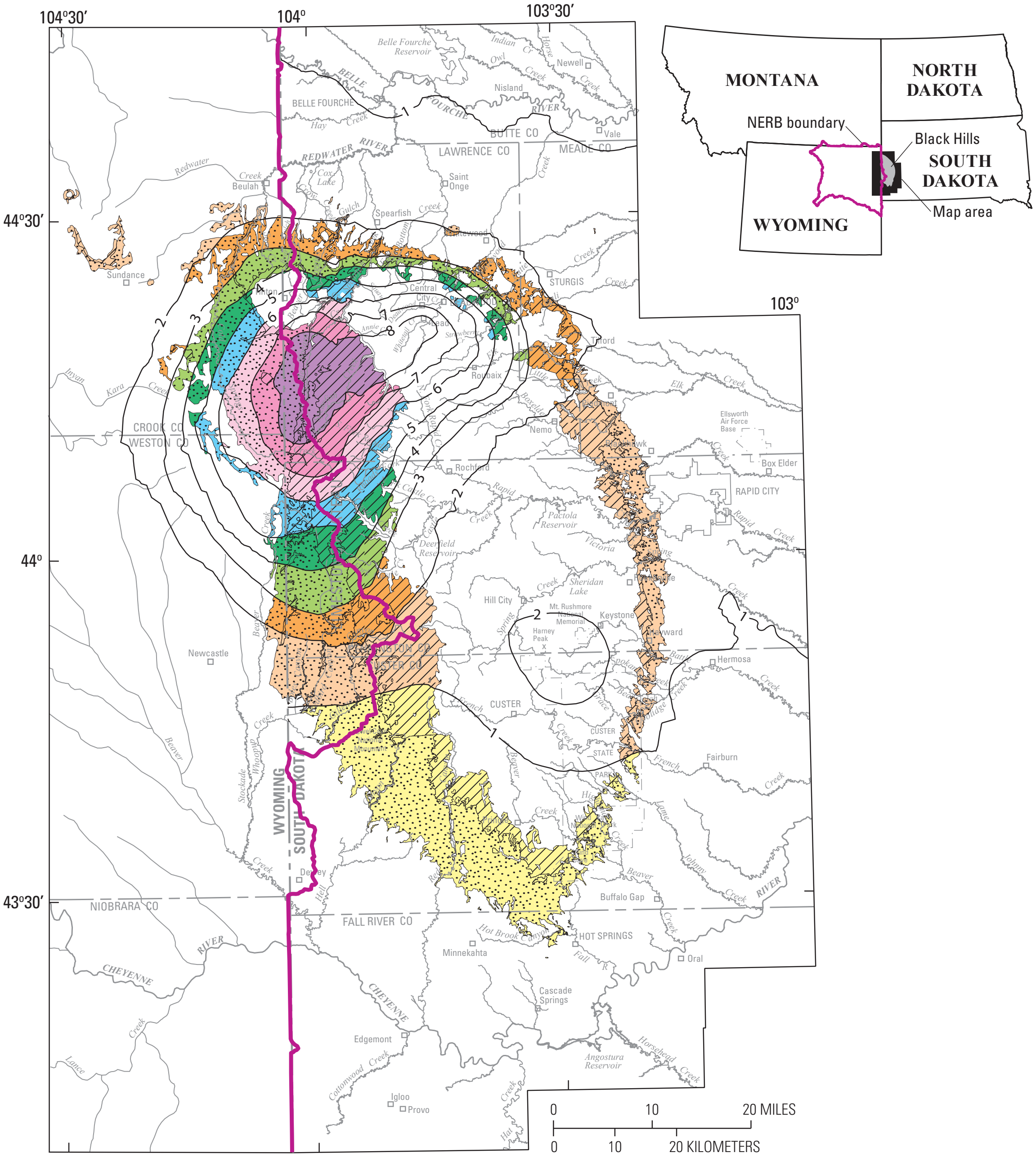
[1]Aquifer outcrop areas for water budgets shown on figure 7–20.

[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).