Chapter 7

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

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

7.1 Platte River Basin

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

Sweetwater Arch:

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

Central Wyoming basins (south):

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

Sierra Madre:

- Sierra Madre

Medicine Bow Mountains:

- Medicine Bow Mountains

Laramie Mountains:

- Laramie Mountains

Central Wyoming basins (north):

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

Great Plains:

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

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

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

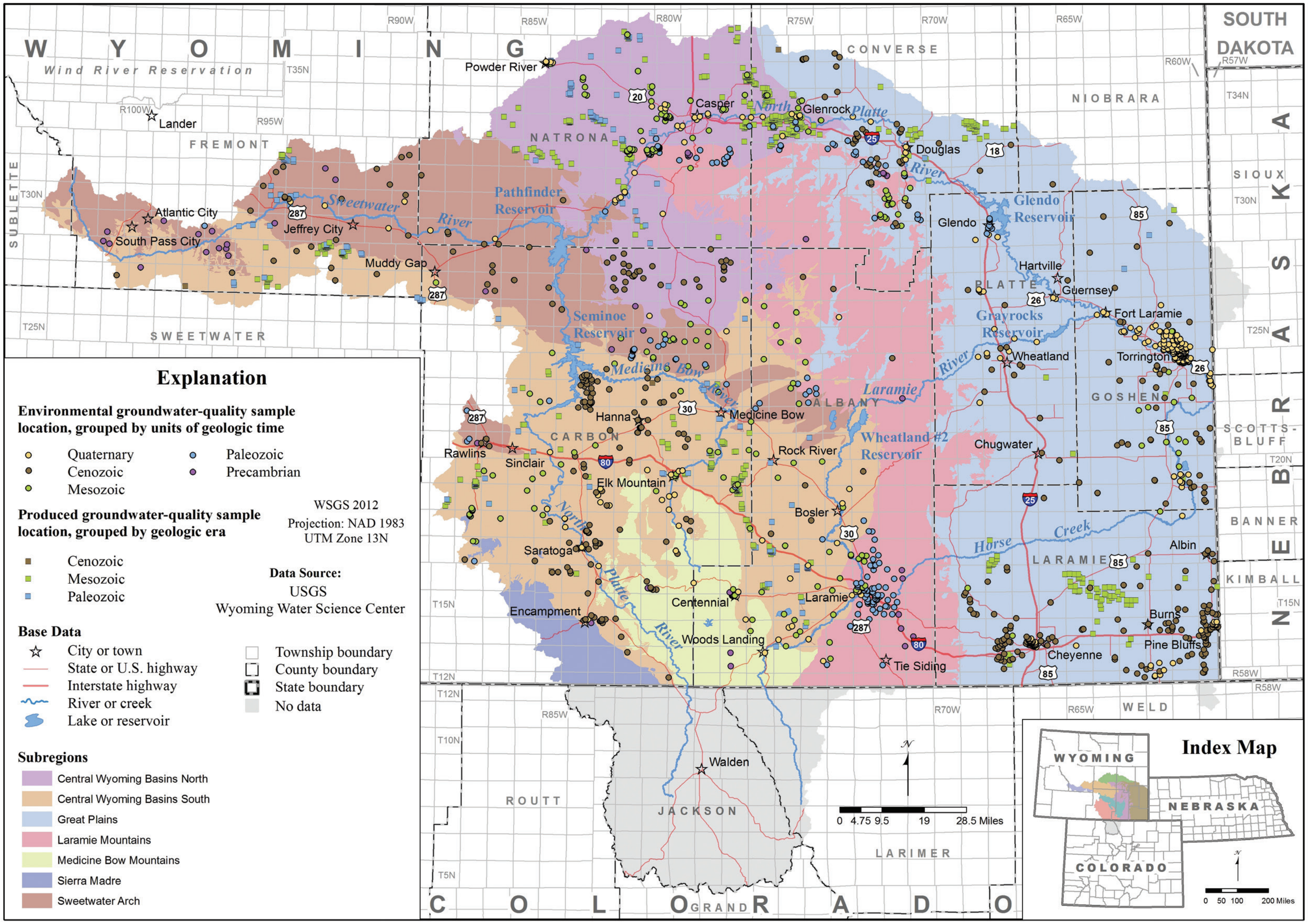


Figure 7-1. Environmental and produced groundwater quality sample locations, grouped by sub-regions, Platte River Basin, Wyoming.

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

7.2 Cenozoic hydrogeologic units

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

7.2.1 Quaternary unconsolidated-deposit aquifers

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

7.2.1.1 Quaternary alluvial aquifers

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

Physical characteristics

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

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

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

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

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

Due to areal extent, location, large saturated thickness, and (or) coarse sediment size, the largest well yields obtained from Quaternary alluvial aquifers in the PtRB are associated with the North Platte River and lower reaches of its major tributaries (Rapp et al., 1957; Morris and Babcock, 1960; Herrmann, 1972, 1976; Crist, 1975; Weston Engineering, 1998b; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein). Aquifers in North Platte River alluvium and immediately adjacent upland terrace deposits [defined as the first, second, and third terraces by Rapp et al. (1957)] are in hydraulic connection throughout much of the North Platte River valley in the vicinity of Torrington. Consequently, the deposits comprise a hydraulically connected groundwater system in the area (Herrmann, 1972, 1976; Crist, 1975; Parks, 1991); Crist (1975) defined this groundwater system as the "valley-fill aquifer." Water obtained from the productive North Platte River alluvial aquifer is used extensively for stock, domestic, and irrigation purposes (for example, Morris and Babcock, 1960; Herrmann, 1972, 1976; Crist, 1975; Parks, 1991; James M. Montgomery Consulting Engineers, Inc., 1990a; Baker and Associates, 1994; Banner Associates, Inc., and TriHydro Corporation, 1995, and references therein; Weston Engineering, 1998b, and references therein; Gollnitz and Clancy, 2002, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007, and references therein). In addition, the productive North Platte River alluvial aquifer is used to provide water to numerous public water supply systems, including the cities and adjacent areas of Casper, Guernsey, Hartville, Fort Laramie, Lingle, and Torrington (James M. Montgomery Consulting Engineers, Inc., 1990a; Parks, 1991; Baker and Associates, 1994; Banner Associates, Inc., and TriHydro Corporation, 1995, and references therein; TST Inc. et al., 1995a, b; Weston Engineering, 1998b; Gollnitz and Clancy, 2002, and references therein; Lidstone and Associates, 2004).

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

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

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

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

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

Chemical characteristics

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

Sweetwater Arch

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

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

Central Wyoming basins (south)

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

Concentrations of some characteristics and constituents in water from Quaternary alluvial aquifers in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (100 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), nitrate (11 percent; USEPA MCL of 10 mg/L), and nitrate plus nitrite (9 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (36 percent; USEPA SMCL of 500 mg/L), sulfate (20 percent; SMCL of 250 mg/L), pH (4 percent above upper SMCL limit of 8.5), fluoride (4 percent; SMCL of 2 mg/L), and chloride (4 percent; SMCL of 250 mg/L).

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

Medicine Bow Mountains

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

Laramie Mountains

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

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

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

Central Wyoming basins (north)

The chemical composition of groundwater in Quaternary alluvial aquifers in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 30 wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram A**). TDS concentrations were variable and indicated that most waters were fresh (47 percent of samples), and remaining waters ranged from slightly to moderately saline (**Appendix E6**; **Appendix G4**, **diagram A**; supplementary data tables). TDS concentrations ranged from 165 to 8,950 mg/L, with a median of 1,110 mg/L.

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

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

Great Plains

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

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

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

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

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

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

7.2.1.2 Quaternary terrace-deposit aquifers

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

Physical characteristics

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

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

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

Where saturated and permeable, Quaternary terrace deposits can contain aquifers. Quaternary terrace-deposit aquifers can produce enough water locally for stock or domestic use, and possibly for small to moderate irrigation use, although well yield likely will fluctuate based on the amount of recharge (for example, Morris and Babcock, 1960; Weeks, 1964). Groundwater in terrace-deposit aquifers typically is unconfined (water-table conditions predominate). Quaternary terrace-deposit aquifers in the Wheatland Flats, Pine Bluffs Lowland, and North Platte River valley areas are important aquifers used to supply water for stock and domestic uses (Rapp et al., 1957; Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Crist and Borchert, 1972). In parts of these areas, sufficient volumes of water can be obtained from Quaternary terrace-deposit aquifers for public-supply or irrigation use due to large saturated thickness, coarse sediment size, and sufficient recharge (Rapp et al., 1957; Lowry and Crist, 1967; Crist and Borchert, 1972). In parts of the PtRB, Quaternary alluvial aquifers and Quaternary terrace-deposit aquifers can be in direct hydraulic connection with one another and (or) with adjacent or underlying Tertiary bedrock aquifers (Morris and Babcock, 1960; Weeks, 1964; Lowry and Crist, 1967; Crist and Borchert, 1972; Crist, 1975, 1980, 1990; Borchert, 1985).

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

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

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

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

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

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

Chemical characteristics

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

Central Wyoming basins (south)

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

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

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

Central Wyoming basins (north)

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

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

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

Great Plains

The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 47 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram B**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram B**; supplementary data tables). TDS concentrations ranged from 234 to 727 mg/L, with a median of 542 mg/L.

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

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

7.2.1.3 Aquifers in Quaternary dune sand (eolian) deposits

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

Physical characteristics

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

Chemical characteristics

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

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

Central Wyoming basins (north)

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

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

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

Great Plains

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

7.2.1.4 Aquifers in Quaternary glacial deposits

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

Physical characteristics

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

Chemical characteristics

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

Central Wyoming basins (south)

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

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

Medicine Bow Mountains

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

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

Groundwater-flow models

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

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

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

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

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

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

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

Weston Engineering (1998b) constructed a groundwater-flow model of the North Platte River alluvial aquifer for the city of Guernsey and adjacent areas. In the study, the alluvial aquifer was defined as an unconfined aquifer composed of saturated Quaternary alluvium. The North Platte River alluvial aquifer was modeled using the finite-difference MODFLOW groundwater-flow model. The groundwater-flow model consisted of two layers—an upper layer composed of the unconsolidated alluvial aquifer and an underlying low-permeability layer composed of two consolidated (bedrock) lithostratigraphic units (Arikaree and Hartville Formations). The groundwater-flow model was constructed to evaluate alluvial aquifer groundwater-flow directions and interaction with the North Platte River for establishment of wellhead protection areas. After the steady-state model was calibrated, the particle tracking program associated with MODFLOW, MODPATH (Pollock, 1994), was used to delineate wellhead protection areas for individual public-supply wells.

7.2.2 Tertiary hydrogeologic units

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

7.2.2.1 High Plains aquifer system

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

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

Lithostratigraphic units

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

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

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

Lithostratigraphic unit of Love et al. (1993)	Hydrogeologic unit of Libra et al. (1981) [Denver-Julesberg Basin, southeastern Wyo.]		Hydrogeologic unit of Crist (1983) [Wheatland Flats area, Platte County, Wyo.]		Hydrogeologic unit of Borchert (1985) [LaGrange area, Goshen and Laramie Counties, Wyo., and small area in western Nebr.]		Hydrogeologic unit of Wyoming Statewide Framework Plan (WWC Engineering et al., 2007, Figure 4-9) [Statewide]	Hydrogeologic unit used in this report (where White River Group or Formation is undivided) [southeastern Wyo.]		Hydrogeologic unit used in this report (where White River Group is divided into Brule and Chadron Formations) [southeastern Wyo.]	
Alluvial and terrace deposits	Quaternary aquifers		Local aquifers[5]	Aquifer[10]	Local aquifers[5]	LaGrange aquifer[11]	Major aquifer-alluvial	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,12]	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,8,13]
Ogallala Formation	Major aquifer	Tertiary aquifer system	Not present in study area		Not present in study area		Major aquifer-sandstone	Ogallala aquifer		Ogallala aquifer	
Arikaree Formation			Aquifer		Not present or not part of LaGrange aquifer		Major aquifer-sandstone	Arikaree aquifer		Arikaree aquifer	
Brule Formation	Aquitard with discontinuous aquifers[6]		Not discussed		Aquifer		Marginal aquifer	White River aquifer/ confining unit[12]		Brule aquifer/confining unit[8]	
Chadron Formation	Aquitard with discontinuous aquifers[6]									Confining unit with local aquifers- Chadron aquifer/ confining unit[8,13]	

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Hydrostratigraphy

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

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

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

Discrepancies in regional aquifer and aquifer system nomenclature (hydrostratigraphy) arise primarily as a result of different interpretations of the hydrogeologic role of the White River Group or Formation in southeastern Wyoming. The Arikaree and Ogallala Formations are defined as aquifers within the High Plains aquifer system throughout their areal extent in southeast Wyoming and adjacent States by all investigators, but the White River Group or Formation (or parts of the unit) is defined as either an aquifer or confining unit, depending upon local hydrogeologic characteristics and (or) whether the "White River" has been elevated to group rank and divided into the Brule and Chadron Formations (**Figure 7-2**). Most investigators, including the USGS RASA program, define the Brule Formation as an aquifer and part of the High Plains aquifer system only where locally permeable and (or) in hydraulic connection with the overlying Ogallala or Arikaree Formations where present; where impermeable, the formation is defined as a confining unit underlying the High Plains aquifer system. Regionally, the USGS does not consider the Chadron Formation underlying the Brule Formation to be part of the High Plains aquifer system, and the unit is classified as a confining unit, a confining unit with local aquifers, or an aquifer underlying the High Plains aquifer system (**Figure 7-2**). However, regional USGS potentiometric-surface maps group the Chadron Formation with the Brule Formation and show both units as part of the aquifer system where exposed at land surface in southeast Wyoming, primarily where the Chadron Formation is exposed at land surface in the Goshen Hole area (**Plate 4; Figure 7-2**) (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Gutentag et al., 1984; Avery and Pettijohn, 1984; Weeks et al., 1988), inferring hydraulic connection with the rest of the aquifer system (see Chadron Formation outcrop area in Goshen Hole on **Plate 4**) and somewhat contradicting the USGS RASA regional definition of the aquifer system. In addition, some local studies (most of which were conducted by the USGS and shown in **Figure 7-2**) consider the Chadron Formation (or parts of the Chadron Formation), where locally permeable, to be in hydraulic connection with adjacent members of the aquifer system in some areas in southeast Wyoming, primarily where the formation is exposed at land surface and located laterally or vertically adjacent to other Tertiary geologic units in the Goshen Hole area (for example, Rapp et al., 1957; Borchert, 1985) or where the "White River" is not elevated to group rank and is defined as a formation (for example, Crist, 1980; Cooley and Crist, 1981). Consequently, the definition of the High Plains aquifer system proposed herein (last two columns in **Figure 7-2**) acknowledges the regional definition of the system by the USGS RASA program while also acknowledging likely local hydraulic connection of the White River Group or Formation (including the Chadron Formation) with other Cenozoic lithostratigraphic units commonly considered part of the aquifer system in parts of southeastern Wyoming.

Aquifer System Physical Characteristics

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

7.2.2.1.1 Ogallala aquifer

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

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

7.2.2.1.2 Arikaree aquifer

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

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

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

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

7.2.2.1.3 White River aquifer/confining unit

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

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

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

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

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

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

Regional groundwater flow, recharge, and discharge

Groundwater in the High Plains aquifer system in southeastern Wyoming generally moves from west to east, but this pattern of flow is altered locally by groundwater divides and by groundwater discharge to streams (**Plate 4**). In southeastern Wyoming, the altitude of the potentiometric surface declines from a high of about 6,800 ft in northwestern Laramie County to a low of about 4,100 ft in the vicinity of Torrington in the North Platte River drainage (**Plate 4**).

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

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

Groundwater-flow models

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

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

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

Crist (1977) constructed a groundwater-flow model of the Arikaree aquifer (composed only of the Arikaree Formation) in an 800-mi.^{2} area in southern Niobrara and northern Goshen Counties near Lusk. A finite-difference model [not published at time of study but subsequently published as Trescott et al. (1976)] was used to evaluate the effects of current and future development (domestic, industrial, and agricultural use) of the aquifer, although pumpage due to then-current and potential future irrigation well development was emphasized. A steady-state model was constructed and calibrated, and predictive transient simulations were made to evaluate irrigation and industrial groundwater withdrawals for water years 1973 to 1993.

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

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

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

Crist (1983) constructed a groundwater-flow model of the Arikaree aquifer in a 260-mi.^{2} area in central Platte County that included the Wheatland Flats area and an adjacent area. In the study, the Arikaree aquifer was divided into an upper and lower aquifer. The upper Arikaree aquifer consisted of saturated Quaternary terrace deposits, saturated alluvium along Rock Creek-Wheatland Creek, Sybille Creek, Laramie River, and Chugwater Creek, and the upper part of the saturated Arikaree Formation to a depth of about 100 ft below land surface; the lower Arikaree aquifer consisted of the saturated Arikaree Formation below a depth of 100 ft below land surface. The groundwater-flow model was constructed to simulate hydrologic conditions in the Wheatland Flats area, including the relation between the Arikaree aquifer and adjacent streams. The Arikaree aquifer was modeled with two layers representing the upper and lower aquifer using the finite-difference model of Trescott (1975) and Trescott et al. (1976) as modified by Hoxie (1977, p. 21-24) to account for the interaction between the aquifer and streams. A steady-state model was constructed and calibrated, and included a water budget. Finally, transient conditions were simulated for the years 1971 to 1978.

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

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

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

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

Lidstone and Anderson (1995) constructed a groundwater-flow model of the Brule aquifer (composed of the Brule Formation) for a 26.5- by 26.5-mile area centered on the city of Pine Bluffs municipal well field. The aquifer was modeled using the Prickett Lonnquist Aquifer Simulation Program (PLASM) finite-difference model (Prickett and Lonnquist, 1971). The groundwater-flow model was constructed to predict cumulative water-level declines over a 20-year period from then-current and potential future withdrawals from six public-supply wells composing the municipal well field. The groundwater-flow model was constructed to only evaluate the effects of withdrawals from the six public-supply wells; withdrawals from non-municipal and high-production irrigation wells in the area were not incorporated into the model.

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

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

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

Chemical characteristics

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

Ogallala aquifer

The chemical composition of groundwater in the Ogallala aquifer in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as 120 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram C**). Most waters were calcium-bicarbonate type. TDS concentrations were variable and indicated that most waters were fresh (97 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters were slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram C**; supplementary data tables). TDS concentrations ranged from 70 to 1,270 mg/L, with a median of 227 mg/L.

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

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

Arikaree aquifer

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

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

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

White River aquifer/confining unit

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

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

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

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

Brule aquifer/confining unit

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

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

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

7.2.2.2 Chadron aquifer/confining unit

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

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

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

7.2.2.3 Bug Formation

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

7.2.2.4 Kortes and Moonstone aquifers

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

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

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

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

7.2.2.5 Aquifers in undifferentiated Miocene rocks and Split Rock aquifer

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

Physical characteristics

Aquifers in undifferentiated Miocene rocks

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

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

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

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

Split Rock aquifer

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

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

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

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

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

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

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

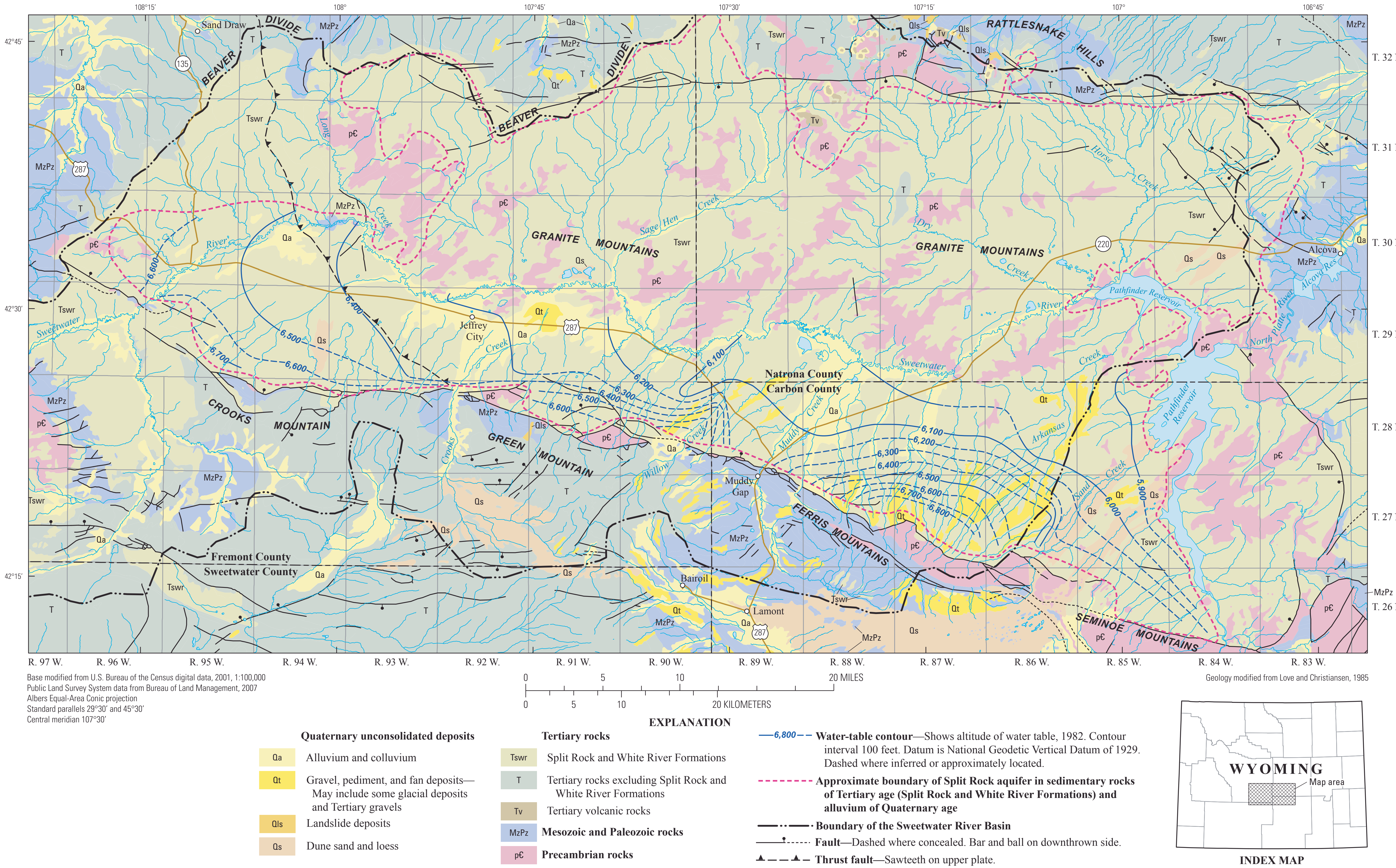


Figure 7-3. Water-table contours for Split Rock aquifer in Sweetwater River Basin, Wyoming (modified from Borchert, 1977, 1987).

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

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

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

Chemical characteristics

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

Sweetwater Arch

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

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

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

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

Central Wyoming basins (south)

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

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

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

7.2.2.6 Browns Park aquifer

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

Physical characteristics

The Browns Park aquifer consists of the Browns Park Formation (**Plate T**) and is present in the southern part of the PtRB, primarily in the Saratoga Valley area and areas to the west (**Plates 1, 2**). The Browns Park Formation contains both fluvial and eolian deposits (Love et al., 1993). Love and Christiansen (1985) showed the Miocene-age Browns Park Formation as well as the late Miocene-age North Park Formation on the statewide geologic map. Vine and Prichard (1959) used the name "North Park Formation" to describe the Miocene rocks of the Miller Hill area. No fossils were found to date the formation, and they felt it could be either the Browns Park Formation or the North Park Formation. Montagne (1991) combined the units as the Browns Park Formation because of the difficulty in establishing a mappable boundary between the two units; this reinterpretation of both units as the Browns

Park Formation was subsequently adopted in the statewide Phanerozoic chart (Love et al., 1993) and is used herein. The hydrogeologic unit described herein includes the Browns Park Formation as well as the rocks formerly assigned to the North Park Formation prior to Montagne (1991).

The Browns Park Formation has varicolored (gray, green, tan, or white) calcareous to siliceous to tuffaceous siltstones and sandstones that contain white pumicite beds, white chalcedonic and algal lacustral limestone ledges, and shaly lacustrine rocks (Powell, 1876; Hansen, 1984; Honey and Izett, 1989; Montagne, 1991). Along the uplifts, there is usually a conglomerate layer (sometimes referred to as the "basal conglomerate") primarily derived from Precambrian rocks in a cross-bedded calcareous sandy matrix (Powell, 1876; Hansen, 1984; Honey and Izett, 1989; Montagne, 1991). The formation probably was deposited by a combination of fluvial, lacustrine, and eolian processes. The Browns Park Formation is as much as 2,500-ft thick in the Saratoga Valley (Montagne, 1991).

The Browns Park aquifer is developed as a water supply for stock, domestic, and agricultural use. Sandstone and conglomerate units primarily yield water to wells completed in the aquifer. The Browns Park aquifer has been defined as a "major aquifer" (Kuhn et al., 1983) or "principal aquifer" (Richter, 1981a). In the general vicinity of the Laramie, Shirley, and Hanna Basins (including Carbon County), Richter (1981a) grouped the Browns Park Formation with other Tertiary-age formations into a single hydrogeologic unit defined as the "Tertiary aquifer." The USGS also defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Wyoming Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Variable spring discharges, well yields, and specific capacity have been reported or measured for the Browns Park aquifer. Visher (1952) reported discharges of 100, 500, and 1,300 gal/min for three springs discharging in the Pass Creek Flats area; the high spring discharges were attributed to faults. Richter (1981a) referred to the spring discharging 1,300 gal/min as the "Lake Creek Spring" and noted that the spring has been developed by the Wyoming Game and Fish Department to supply water to the Saratoga Fish Hatchery. Lowry et al. (1973, Sheet 3) reported yields of 500 to 1,000 gal/min for wells completed in Tertiary hydrogeologic units in the Laramie, Shirley, and Hanna Basins, including the Browns Park Formation in Carbon County. In addition to interstitial permeability, Lowry et al. (1973, Sheet 3) noted that high yields reported for some wells and springs were likely attributable to development of secondary permeability. Richter (1981a) reported well yields ranging from 1 to 300 gal/min, and Collentine et al. (1981) reported well yields ranging from 2.5 to 30 gal/min. In the Saratoga Valley area, wells yielding hundreds of gallons of water per minute are used for agriculture to supplement surface-water irrigation (Lenfest, 1986; Crist, 1990). Lowry et al. (1973, Sheet 3) attributed the high yields to the large saturated thickness of the formation in the area.

In the vicinity of the Miller Hill and upper Sage Creek areas south of Rawlins, medium to large springs supply much of the water supply for the city of Rawlins. Consequently, Berry (1960, p. 24) reported that "the Browns Park Formation is one of the best aquifers in the Rawlins area." He noted that one spring flowed at a rate as high as 343 gal/min. Berry (1960, p. 24) attributed all spring flows to the "basal conglomerate" of the formation and noted that the springs "maintain the base (low) flow of streams in the southern part of the area." Berry (1960, p. 24-25) speculated that the "basal conglomerate" of the Browns Park Formation in the area had much water production potential and noted that the upper part of the Browns Park Formation in the same area had the potential to "yield moderate to large supplies of water." Subsequent investigation of the "basal conglomerate" in the same area has noted little potential for development of the unit in the same Miller Hill/upper Sage Creek area. Exploratory drilling indicated that the basal conglomerate was a poorer aquifer than the overlying upper part of the Browns Park Formation in the area, as low fluid losses and lithologies encountered during drilling indicated low permeability and poor yield for development as a public water supply (James M. Montgomery, Consulting Engineers, 1983b, p. 3-11). In addition, upon review of earlier work by Vine and Prichard (1959), the investigators believed the springs actually discharge from the upper part of the Browns Park Formation, not the basal conglomerate as reported by Berry (1960).

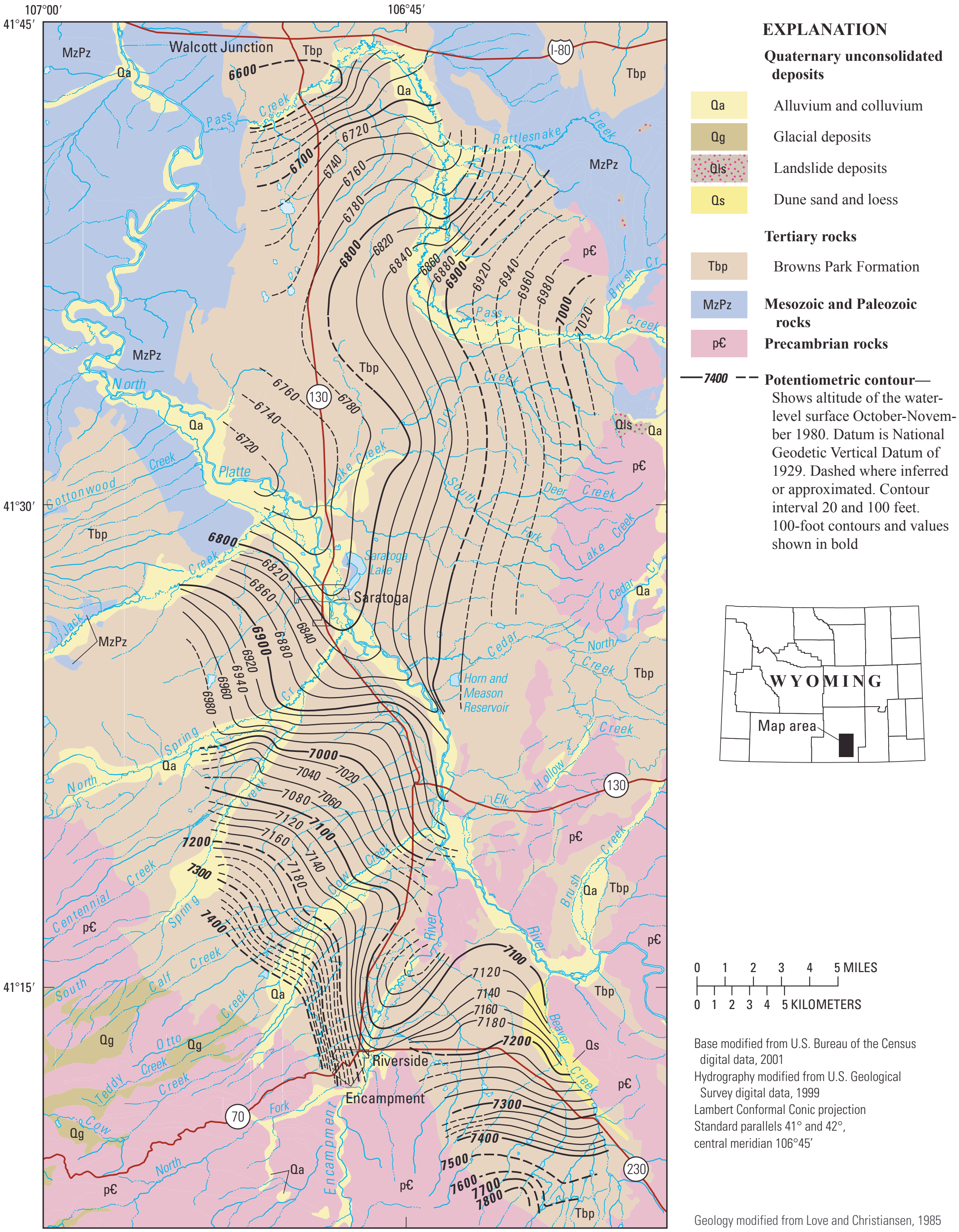


Figure 7-4. Potentiometric surface of the Browns Park aquifer in the Saratoga Valley area, Carbon County, Wyoming (modified from Crist, 1990).

These springs are still an important part of the water supply for Rawlins, but wells have been drilled into other hydrogeologic units (Cloverly and Nugget aquifers) in the Rawlins Uplift area to provide additional water for the city (James M. Montgomery, Consulting Engineers, 1983a, b; 1986a, b, and references therein).

Aquifer tests for wells completed in the Browns Park aquifer have been reported by several previous investigators. Transmissivity values for the Browns Park aquifer west of the Saratoga Valley (west of R. 86 W.) were reported to be lower than transmissivity values in the Saratoga Valley area (Collentine et al., 1981). Aquifer tests by Simons, Li, and Associates (1982a, b) and Howard, Needles, Tammen, and Bergendoff (1984) indicated that the Browns Park aquifer was confined or semiconfined at the locations examined by the investigators.

The direction of groundwater flow in the Browns Park aquifer in the Saratoga Valley area is shown on potentiometric-surface maps by Lenfest (1986, Plate 2) and Crist (1990, Plate 2). Simons, Li, and Associates (1982a) constructed a potentiometric-surface map for part of the area mapped by Lenfest (1986) and Crist (1990), including the area near Encampment and Riverside. The interpreted direction of groundwater flow is similar in all three maps. The potentiometric-surface map from Crist (1990) is reproduced herein as **Figure 7-4**. Groundwater flow is assumed to be perpendicular to the potentiometric contours and the direction of "movement generally is from the edges of the valley toward the North Platte River" (Crist, 1990, p. 9). All of these investigators noted that aquifers in Quaternary unconsolidated deposits along streams were in hydraulic connection with the Browns Park aquifer, so they mapped both units as a single aquifer in the Saratoga Valley area.

Chemical characteristics

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

Central Wyoming basins (south)

The chemical composition of groundwater in the Browns Park aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 59 wells, two test holes, and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram B**). TDS concentrations were variable and indicated that most waters were fresh (81 percent of samples had TDS concentration less than or equal to 999 mg/L), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram B**; supplementary data tables). TDS concentrations ranged from 153 to 3,410 mg/L, with a median of 385 mg/L.

Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (83 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), arsenic (20 percent; MCL of 10 μg/L), gross alpha radioactivity (17 percent; MCL of 15 pCi/L), fluoride (14 percent; MCL of 4 mg/L), nitrate plus nitrite (9 percent; MCL of 10 mg/L), and uranium (9 percent; MCL of 30 μg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: manganese (40 percent; USEPA SMCL of 50 μg/L), TDS (36 percent; SMCL of 500 mg/L), sulfate (29 percent; SMCL of 250 mg/L), aluminum (25 percent exceeded lower SMCL limit of 50 μg/L), fluoride (18 percent; SMCL of 2 mg/L), iron (8 percent; SMCL of 300 μg/L), pH (3 percent above upper SMCL limit of 8.5), and chloride (2 percent; SMCL of 250 μg/L). Aluminum is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (31 percent; WDEQ Class II standard of 200 mg/L), chloride (19 percent; WDEQ Class II standard of 100 mg/L), gross alpha radioactivity (17 percent; WDEQ Class II standard of 15 pCi/L), SAR (11 percent; WDEQ Class II standard of 8), manganese (7 percent; WDEQ Class II standard of 200 μg/L), boron (6 percent; WDEQ Class II standard of 750 μg/L), TDS (3 percent; WDEQ Class II standard of 2,000 mg/L), and pH (2 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents measured at concentrations greater than livestock-use standards were mercury (the one uncensored sample analyzed for the constituent; WDEQ Class III standard of 0.05 μg/L; supplementary data tables), gross alpha radioactivity (17 percent; WDEQ Class III standard of 15 pCi/L), and pH (3 percent above upper WDEQ Class III limit of 8.5). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics.

The chemical composition of groundwater in the Browns Park aquifer in the CBS also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (1,290 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based standards. TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs), and sulfate and chloride exceeded agricultural-use (WDEQ Class II) standards. No characteristics or constituents exceeded State of Wyoming livestock (WDEQ Class III) standards.

Vine and Prichard (1959) collected samples from 25 springs discharging from the Browns Park aquifer (referred to as North Park Formation in their report) in the Miller Hill area. The investigators were evaluating the uranium potential of the formation in the area, so all samples were analyzed for uranium. Reported uranium concentrations for the 25 springs ranged from 2 to 14 μg/L, all less than the current USEPA MCL of 30 μg/L.

Medicine Bow Mountains

The chemical composition of groundwater in the Browns Park aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E4**. TDS concentrations indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 45 to 220 mg/L, with a median of 115 mg/L.

Concentrations of some characteristics and constituents in water from the Browns Park aquifer in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed MCL, but did not exceed the alternative MCL), copper (50 percent; MCL (action level) of 1,300 μg/L), and lead (50 percent; MCL (action level) of 15 μg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: copper (50 percent; SMCL of 1,000 μg/L), iron (50 percent), and pH (17 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the MBM. The one constituent in environmental water samples measured at concentrations greater than agricultural-use standards was copper (50 percent; WDEQ Class II standard of 200 μg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were copper (50 percent of samples analyzed for the constituent; WDEQ Class III standard 500 μg/L), lead (50 percent; WDEQ Class III standard of 100 μg/L), and pH (17 percent below lower WDEQ Class III limit of 6.5).

7.2.2.7 White River aquifer and confining unit (not associated with the High Plains aquifer system)

The physical and chemical characteristics of the White River aquifer and confining unit not associated with the areally extensive High Plains aquifer system in the eastern part of the PtRB are described in this section of the report.

Physical characteristics

The White River aquifer and confining unit not associated with the areally extensive High Plains aquifer system in the eastern part of the PtRB consists of the White River Formation (**Plates J, T,** and **U**). The White River Formation has small areal extent outside of the area in the PtRB associated with the High Plains aquifer system. Outside of the High Plains aquifer system, the White River Formation is present primarily in the southeastern part of Wind River Structural Basin (WRB) that falls within the PtRB, including the northeastern flank of the Granite Mountains; in the Shirley Basin area; and along the northeastern flank of the Laramie Mountains (**Plates 1, 2**). Characteristics of the White River Formation along the northeastern flank of the Laramie Mountains are the same as described in the High Plains aquifer system part of this report, so the reader is referred to that section of the report for description of the unit in that area.

In the southeastern WRB (**Plates 1, 2, Figure 3-1**), the White River Formation is composed of fine-grained sandstone with interbedded layers of tuff and bentonite, and discontinuous lenses of arkose and conglomerate (Van Houten, 1964; Whitcomb and Lowry, 1968; Richter, 1981b, Table IV-1, and references therein). Reported thickness of the White River Formation in the southeastern WRB ranges from 0 to 650 ft (Van Houten, 1964).

In the Shirley Basin and adjacent areas (**Plates 1, 2**), Harshman (1968, 1972) and Denson and Harshman (1969) described the upper part of the White River Formation as interbedded light-tan to light-brown tuffaceous (volcanic) siltstone, sandstone, and conglomerate, and the lower part of the formation as light-pink to light-tan tuffaceous siltstone and claystone. Harshman (1968, 1972) noted that the basal layer in some areas is a red, brown, or green claystone and in other areas the layer is a tuff and sandstone. The upper part is of fluvial origin and the lower part is of fluvial and lacustrine origin. The upper and lower parts are separated by a short interval of non-deposition (Harshman, 1968, 1972). The formation is as much as 850-ft thick in the Shirley Basin area.

Groundwater in the White River aquifer in the southeastern WRB is likely unconfined or semiconfined (Richter, 1981b). Richter (1981b, Table IV-1) reported that the aquifer was highly permeable and productive in the WRB and had "good intergranular permeability and porosity."

The White River Formation contains an important aquifer in the Shirley Basin, and Richter (1981a, p. 54) defined the formation as the "principal water-bearing unit in the Shirley Basin." Richter (1981a, Figure II-6, p. 20) also grouped the White River Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a more broadly defined hydrogeologic unit identified as the "Tertiary aquifer," and as a "principal aquifer." Permeability of coarse-grained lithologies was reported to be primarily intergranular. The USGS also defined the White River aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "lower Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Harshman (1972) examined the groundwater hydrology and quality of aquifers in the White River, Wind River, and Wagon Bed Formations in the Shirley Basin because of the discovery of uranium in the Wind River Formation. As part of the study, potentiometric contours were constructed showing groundwater flow in the aquifers (reproduced with modifications in **Figure 7-5**). Aquifers in all

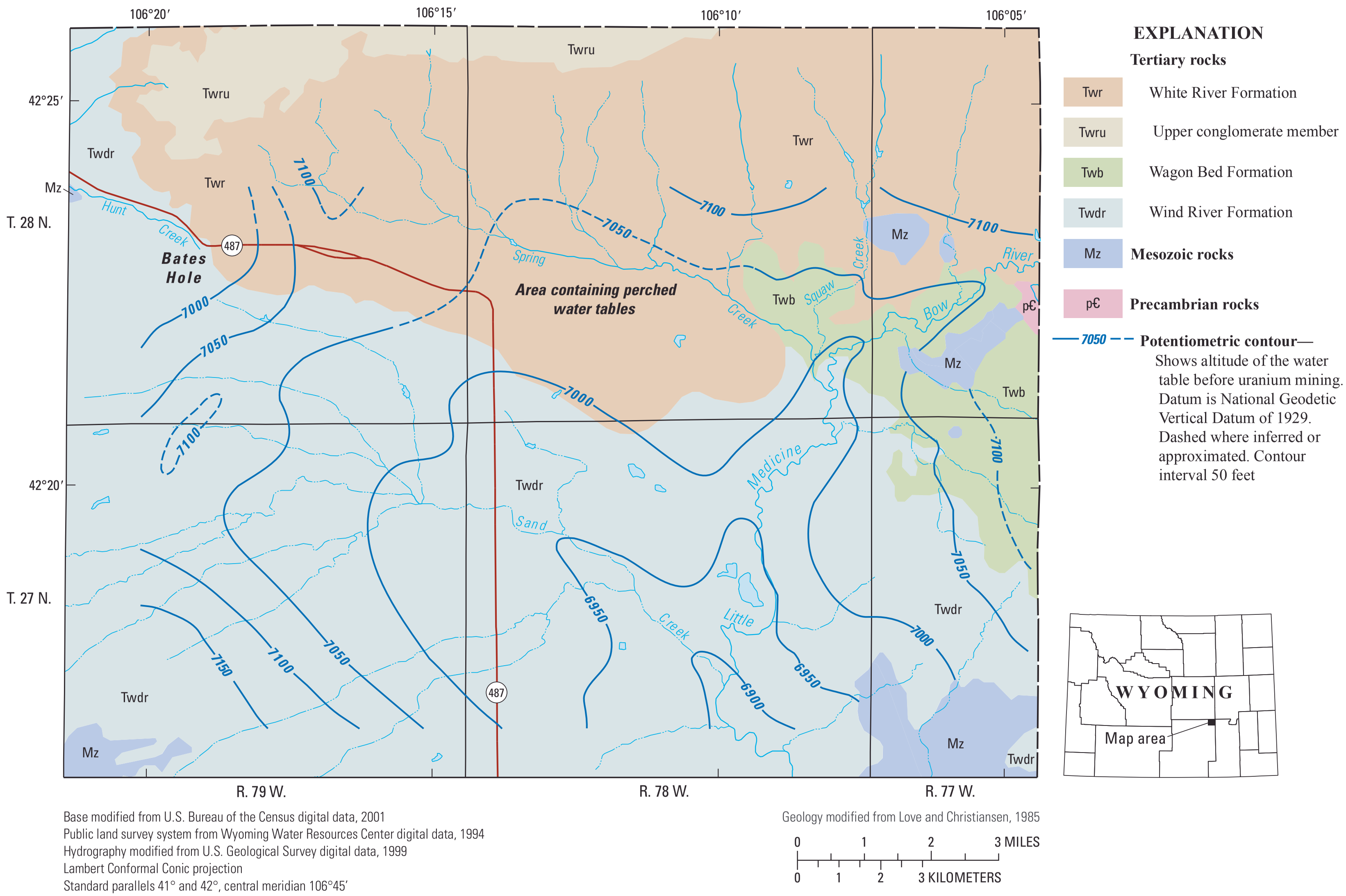


Figure 7-5. Pre-mining potentiometric surface of aquifers in Tertiary hydrogeologic units for a part of the Shirley Basin, Carbon County, Wyoming (modified from Harshman, 1972).

three formations were mapped as a single aquifer in the area, inferring hydraulic connection among the formations in the area. Harshman noted that groundwater in the White River aquifer, and in aquifers in the other formations, was unconfined and that shallow groundwater in the White River aquifer was perched (**Figure 7-5**). He also stated that Spring Creek "is fed from and flows on a perched body of water" and that "it is a gaining stream with respect to the perched water, but it may be a losing stream with respect to the main body of groundwater" (Harshman, 1972, p. 37). Harshman collected groundwater samples from eight springs discharging from the White River Formation (aquifer) to characterize waters in the area. TDS ranged from 178 to 235 mg/L, and water was classified into two groups. Groundwater samples from the first group (group 1) were collected near the base of the upper member of the White River Formation and samples from the second group (group 2) were collected near the base of the lower member. Although ionic composition was similar in both groups, and bicarbonate was the predominant anion in both groups, Harshman (1972, p. 41) noted that water from the lower member (group 2) "contains more sodium, sulfate, and uranium and somewhat less phosphate than does that from the upper member." Total radium concentrations ranged from less than 0.1 to 3.5±0.7 pCi/L, and uranium concentrations ranged from 7.8±0.8 to 52±5 µg/L. One reported uranium concentration exceeded the USEPA MCL of 30 µg/L; several other reported uranium concentrations approached but did not exceed the standard.

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the White River aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 216 to 397 mg/L, with a median of 282 mg/L. On the basis of the few characteristics and constituents analyzed for, the quality of water from White River aquifer in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the White River aquifer in the central Wyoming basins (south) CBS was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Summary statistics calculated for available constituents are listed in **Appendix E2**. The TDS concentrations (220 and 235 mg/L) indicated the waters were fresh (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the White River aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, most water was suitable for domestic use. The concentration of one constituent (arsenic) in one sample exceeded health-based standards for domestic use (USEPA MCL of 10 µg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the White River aquifer in the central Wyoming basins (north) CBN was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and 15 springs. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram B**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E6**; **Appendix G4**, **diagram B**; supplementary data tables). TDS concentrations ranged from 69 to 400 mg/L, with a median of 191 mg/L.

Concentrations of some characteristics and constituents in water from the White River aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for domestic use. Concentrations of one characteristic exceeded aesthetic standards for domestic use (USEPA SMCL) and livestock-use (WDEQ Class III) standards: pH (12 percent below lower limit of 6.5 and 6 percent above upper limit of 8.5). Concentrations of one characteristic was measured at greater than State of Wyoming agricultural-use standards: pH (6 percent above upper WDEQ Class II limit of 9.0).

7.2.2.8 Bishop conglomerate

Little information is available describing the hydrogeologic characteristics of the Oligocene Bishop Conglomerate. Welder and McGreevy (1966, Sheet 3) and Welder (1968, Sheet 2) reported that the potential for groundwater development in the Bishop Conglomerate is not known, but is likely poor to fair. Welder (1968, Sheet 2) indicated that the deposits generally are topographically high and, consequently, probably well-drained in most areas. Little hydrogeologic information is available describing Bishop Conglomerate, but two well-yield measurements were located and are listed on **Plate 3**.

7.2.2.9 Bridger confining unit

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

Physical characteristics

The Bridger confining unit consists of the Eocene Bridger Formation and is present in the Great Divide Basin (**Plates 1, 2**). The Bridger Formation is composed of tuffaceous sandstone, claystone, lenticular marlstone, and conglomerate (Love and Christiansen, 1985, Sheet 2). Although considered an aquifer in the Green River Basin to the west, the Bridger Formation is defined as a confining unit in the Great Divide Basin (Collentine et al., 1981; Glover et al., 1998; Bartos et al., 2010, Figure 5-2). Little hydrogeologic information is available describing the Bridger confining unit in the PtRB study area, but well-yield and other hydraulic properties are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Bridger confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (252 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Bridger confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (pH above upper USEPA SMCL limit and WDEQ Class III limit of 8.5) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (pH above upper WDEQ Class II limit of 9.0 and SAR greater than WDEQ Class II standard of 8) exceeded the State of Wyoming agricultural-use standards.

7.2.2.10 Laney confining unit

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

Physical characteristics

The Laney confining unit consists of the Eocene Laney Member of the Green River Formation and is present in the Great Divide Basin (**Plates 1, 2**). The Laney Member of the Green River Formation is composed of shale and marlstone (Love and Christiansen, 1985, Sheet 2). Although considered an aquifer in the Green River Basin to the west, the Laney Member of the Green River Formation was defined as a confining unit in the Great Divide Basin in previous studies (Collentine et al., 1981; Glover et al., 1998; Bartos et al., 2010, **Figure 5-2**). Little hydrogeologic information is available describing the Laney confining unit in the PtRB study area, but two well-yield measurements were located and are listed on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Laney confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (563 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Laney confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) exceeded aesthetic standards (USEPA SMCL of 500 mg/L) for domestic use. No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.11 Wagon Bed aquifer and confining unit

The physical and chemical characteristics of the Wagon Bed aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Wagon Bed aquifer and confining unit consists of the Wagon Bed Formation (Plates **J, K,** U) and is present only in a small part of the PtRB (**Plates 1, 2**). Harshman (1968, 1972) and Denson and Harshman (1969) described the formation as light-tan to light-gray, very coarse-grained sandstone that is well cemented with a clay binder, and pale-green silicified claystone. Thin-bedded freshwater limestone is present in the lower part of the formation (Harshman, 1968, 1972). Van Houten (1964) reported that the formation was deposited on warm, humid, poorly drained lowlands, flood plains, and lakes of the middle and late Eocene Epoch. The formation is as much as 160-ft thick in the PtRB.

Harshman (1972) examined the groundwater hydrology and quality of aquifers in the White River, Wagon Bed, and Wind River Formations in the Shirley Basin because of the discovery of uranium in the Wind River Formation. As part of the study, a potentiometric-surface map was constructed to show groundwater flow in the aquifers (reproduced with modifications herein as **Figure 7-5**). Aquifers in all three formations were mapped as a single aquifer in the area, inferring hydraulic connection among the formations in the area. The potentiometric contours constructed near the Little Medicine Bow River show that the stream gains flow from the Wagon Bed Formation (aquifer) in the area (**Figure 7-5**).

The Wagon Bed Formation is not permeable everywhere. Crist and Lowry (1972) considered the Wagon Bed Formation in Natrona County to be a confining unit with locally permeable zones. In the Wind River Basin and Granite Mountains area, Richter (1981b) classified the Wagon Bed Formation as a leaky confining unit (**Plate J**). Because permeability of the Wagon Bed Formation depends upon location examined, the formation is classified as an aquifer and confining unit herein (**Plates J, K,** and **U**). Hydrogeologic data describing the Wagon Bed aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Sweetwater Arch

The chemical composition of groundwater in the Wagon Bed aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations (233 and 331 mg/L) indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables).

On the basis of the few characteristics and constituents analyzed for, the quality of water from Wagon Bed aquifer and confining unit in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards

Central Wyoming basins (north)

The chemical composition of groundwater in the Wagon Bed aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations indicated that waters were fresh (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 213 to 310 mg/L, with a median of 310 mg/L.

On the basis of the few characteristics and constituents analyzed for, the quality of water from Wagon Bed aquifer and confining unit in the CBN was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.2.12 Ice Point Conglomerate

The Eocene Ice Point Conglomerate (**Plate J**) consists of reddish-brown conglomerate composed primarily of Paleozoic rock fragments (Love and Christiansen, 1985, Sheet 2). In the PtRB, the Ice Point Conglomerate is exposed at land surface only in a very small area on the southern Granite Mountains north of the Great Divide Basin (**Plates 1, 2**). No information describing the hydrogeologic characteristics of the unit was located, but on the basis of the description of the distribution and thickness of the conglomerate by Love (1970, p. C59), it is possible that the formation consists of little more than thin lag deposits that are likely unsaturated.

7.2.2.13 Crooks Gap Conglomerate

The physical and chemical characteristics of the Crooks Gap Conglomerate in the PtRB are described in this section of the report.

Physical characteristics

The Eocene Crooks Gap Conglomerate (**Plate J**) consists of giant granitic boulders in an arkosic sandstone matrix (Love and Christiansen, 1985, Sheet 2). In the PtRB, the Crooks Gap Conglomerate is exposed at land surface only in a very small area on the southern Granite Mountains north of the Great Divide Basin (**Plates 1, 2**). Little hydrogeologic information is available for the Crooks Gap Conglomerate likely because of very limited areal extent. One spring discharge measurement was located and is presented on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Crooks Gap Conglomerate in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (73 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Crooks Gap Conglomerate in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for domestic use. Concentrations of one constituent (mercury) exceeded State of Wyoming agriculture water-quality standards (the WDEQ Class III standard of 0.05 μg/L is more stringent than the EPA MCL of 2 μg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.2.2.14 Battle Spring aquifer

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

Physical characteristics

The Battle Spring aquifer consists of the Battle Spring Formation, which is present at or near land surface in parts of the eastern part of the Great Divide Basin in the PtRB (**Plates 1, 2**). Bradley (1961) described the Battle Spring Formation as being composed of "light gray to brown, coarse-grained to pebbly arkosic sandstone with a lesser amount of greenish gray sandy clay and mudstone; locally contains large spheroidal concretions; interfingers with the Wasatch and Green River Formations." Pipiringos (1961, p. A34-A35) suggested that the sediments composing the Battle Spring Formation were deposited in deltaic sheets associated with one of the ancient Green River lakes, and that the source of the sediment was the Granite Mountains. However, Masursky (1962, p. 10-11) and Love (1970, p. C33-C34) believed that the Battle Spring Formation mapped by Pipiringos (1955, 1961) was a mountainward fluvial facies of the main body of the Wasatch Formation and should not be considered a separate formation. Welder and McGreevy (1966, Sheet 3) reported that the Battle Spring Formation ranges in thickness from "1,000 to about 4,500 ft."

The Battle Spring Formation contains an important aquifer in the Great Divide Basin, although its extent is very limited in the PtRB. Collentine et al. (1981, Figure III-6, p. 28) combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit and defined the combined unit as a "principal aquifer" in the Great Divide and Washakie Basins. Similarly, Naftz (1996) and Glover et al. (1998) also combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit, but also included the Fort Union Formation; this unit was defined as the "Wasatch-Fort Union aquifer," and the Wasatch and Battle Spring Formations were combined and defined as a subaquifer defined as the "Wasatch zone" of the Wasatch-Fort Union aquifer. The USGS also defined the Battle Spring aquifer as a "principal aquifer" (Whitehead, 1996) and combined the aquifer with many others that comprise the "Colorado Plateaus aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Welder and McGreevy (1966) and Collentine et al. (1981) described the hydrogeologic characteristics of the Battle Spring aquifer throughout the Great Divide Basin. Welder and McGreevy (1966, Sheet 3) reported good development possibilities in the northeast part of the Great Divide Basin and noted "maximum yields of wells penetrating the entire formation might exceed 1,000 gal/min." Collentine et al. (1981, p. 52) reported that the aquifer is "capable of yielding at least 150 gal/min to water wells, though most yields generally range from 30 to 40 gal/min."

Chemical characteristics

The chemical composition of groundwater in the Battle Spring aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentrations (160 and 225 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L).

Concentrations of some characteristics and constituents in water from the Battle Spring aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, all water was suitable for domestic use. Concentrations of one constituent (iron) exceeded aesthetic standards for domestic use (USEPA SMCL of 300 μg/L). No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.15 Wind River aquifer

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

Physical characteristics

Present primarily in the southerneastern part of the Wind River Structural Basin that falls within the PtRB study area, the Granite Mountains area, and the Laramie and Shirley Basins, the Wind River aquifer consists of the Eocene Wind River Formation (**Plates 1, 2; Plates J, K, U**) (Bartos et al., 2012, and references therein). Thickness of the Wind River Formation in the WRB ranges from about 100 ft along mountain flanks to about 5,000 ft in the central basin (Bartos et al., 2012, and references therein). The Wind River Formation is as much as 500-ft thick in the Laramie and Shirley Basins (Richter, 1981a, Table IV-1). The Wind River Formation is composed of an interbedded sequence of claystone, shale, siltstone, and conglomerate, with lenticular beds of fine- to coarse-grained sandstone of variable thickness and areal extent; small amounts of bentonite, tuff, and limestone also may be present (Morris et al., 1959; McGreevy et al., 1969; Richter, 1981a, b). Coarser deposits may be more abundant along the basin margins because of proximity to sediment sources such as the Wind River Mountains (Whitcomb and Lowry, 1968).

In the WRB, the Wind River aquifer is underlain by the Indian Meadows confining unit or by the Fort Union aquifer, in the absence of the Eocene Indian Meadows Formation (Bartos et al., 2012, Plate II). In the Wind River Mountains, the Wind River Formation may be underlain by the Conglomerate of Roaring Fork (Bartos et al., 2012, Plate II). Where buried in the WRB, the aquifer is overlain by the Aycross-Wagon Bed confining unit [composed of the volcaniclastic Eocene Tepee Trail and Aycross Formations or siliciclastic Wagon Bed Formation (Bartos et al., 2012, Plate II)], or Quaternary unconsolidated deposits (Bartos et al., 2012, Plate II). In the Laramie and Shirley Basins, the Wind River aquifer is overlain by the Wagon Bed aquifer and confining unit (where buried) and underlain by the Fort Union or Hanna aquifers (**Plates J, U**). In the Granite Mountains area, the Wind River aquifer is overlain by the Crooks Gap Conglomerate or Wagon Bed aquifer and confining unit (defined as the Aycross-Wagon Bed confining unit in Bartos et al., 2012), depending upon which unit is present in the area examined (**Plates 1, 2; Plate J**).

The Wind River aquifer is used as a source of water for domestic, stock, irrigation, industrial, and public-supply purposes throughout the WRB (Richter, 1981a, b; Bartos et al., 2012). Many wells are installed in the Wind River aquifer in the WRB because it is present at or near land surface (crops out) throughout most of the basin. Because of limited areal extent, the aquifer is much less used in the PtRB. Where present in the Laramie and Shirley Basins, few wells are completed in the aquifer because of the sparse population in the vicinity of the aquifer outcrop. Regardless of location, most wells completed in the Wind River aquifer are for stock and domestic use because of relatively low yields and water quality that may preclude some uses without treatment (Morris et al., 1959; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981a, b; Bartos et al., 2012). Hydrogeologic data describing the Wind River aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate 3**. Regional groundwater flow in the Wind River aquifer in the southeastern WRB within the PtRB area is "toward the east with flow converging on Alcova and Pathfinder Reservoirs" (Richter, 1981b, p. 83).

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Wind River aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E1**. On the basis of the one characteristic analyzed for, the quality of water from the Wind River aquifer in the SA was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Wind River aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples), and remaining waters were moderately saline (TDS concentrations between 3,000 and 9,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 292 to 6,450 mg/L, with a median of 980 mg/L.

Concentrations of some characteristics and constituents in water from the Wind River aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (67 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), chloride (67 percent; SMCL of 250 mg/L), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent of samples analyzed for the constituent; WDEQ Class II standard 8), chloride (67 percent; WDEQ Class II standard of 100 mg/L), sulfate (67 percent; WDEQ Class II standard of 200 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L).

Central Wyoming basins (north)

The chemical composition of groundwater in the Wind River aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 12 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations indicated that most waters were fresh (93 percent of samples), and remaining waters were slightly saline (TDS ranging from 1,000 to 2,999 mg/L) (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 82 to 1,310 mg/L, with a median of 346 mg/L.

Concentrations of some characteristics and constituents in water from the Wind River aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: aluminum (the concentration in the one sample analyzed for this constituent exceeded the SMCL limits of 50-200 μg/L), TDS (29 percent), and sulfate (29 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. The concentration of one constituent in environmental water samples exceeded agricultural-use standards: sulfate (29 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.2.2.16 Wasatch aquifer

The physical and chemical characteristics of the Wasatch aquifer in the PtRB are described in this section of the report. Because of different geologic characteristics and hydrogeologic nomenclature in the two areas where the Wasatch Formation is present in the PtRB (Great Divide Basin and southern Powder River Basin; **Plate 1**), discussion of the Wasatch aquifer is divided into these two geographic areas.

Physical characteristics

Great Divide Basin (central Wyoming basins (south)

The Wasatch Formation, which contains the Wasatch aquifer, is composed of fluvial sediment that was deposited during the same period as the Green River Formation. In the early and middle Eocene Epoch, Lake Gosiute repeatedly expanded and contracted. Fluvial sediments of the Wasatch Formation were deposited around the margins of the lake basin in a belt that narrowed when the lake expanded and widened when the lake contracted (Bradley, 1964, p. A18).

The main body of the Wasatch Formation is present at or near land surface around the perimeter of the Washakie Basin. Masursky (1962, p. 10-11) believed that the Battle Spring Formation mapped by Pipiringos (1955, 1961) was really just a mountainward fluvial facies of the main body of the Wasatch Formation. Love (1970, p. C33-C34) supported this assessment. The Battle Spring Formation is present at or near land surface in much of the eastern part of the Great Divide Basin. The upper parts of the main body of the Wasatch Formation intertongue with tongues and members of the Green River Formation. The lower part of the main body of the Wasatch Formation predates Lake Gosiute, and underlies the Green River Formation, rather than intertonguing with it. Love and Christiansen (1985) described the main body of the Wasatch Formation in southwest Wyoming as “drab sandstone, drab to variegated claystone and siltstone; locally derived conglomerate around basin margins.” Like the rest of the Wasatch Formation, the main body of the Wasatch Formation is composed of fluvial sediment deposited in the same basin occupied by Lake Gosiute. The main body of the Wasatch Formation is more than 4,000-ft thick in parts of the Green River and Washakie Basins (Roehler, 1992, p. E26–E27).

The Wasatch Formation contains an important aquifer in the Great Divide and Washakie Basins. Collentine et al. (1981, Figure III-6, p. 28) combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit and defined the combined unit as a “principal aquifer” in the Great Divide and Washakie Basins. Similarly, Naftz (1996) and Glover et al. (1998) also combined the Wasatch and Battle Spring Formations into a single hydrogeologic unit, but also included the Fort Union Formation; this unit was defined as the “Wasatch-Fort Union aquifer” and the Wasatch and Battle Spring Formations were combined and defined as a subaquifer defined as the “Wasatch zone” of the Wasatch-Fort Union aquifer. The USGS also define the Wasatch aquifer as a “principal aquifer” (Whitehead, 1996) and combined the aquifer with many others that comprise the “Colorado Plateaus aquifers” category on the national principal aquifers map (U.S. Geological Survey, 2013).

Individual discontinuous sandstone beds or lenses compose the Wasatch aquifer (Welder and McGreevy, 1966; Collentine et al., 1981). Welder and McGreevy (1966) reported that well yields for 90 wells in the Great Divide and Washakie Basins and surrounding areas ranged from 5 to 250 gal/min. The investigators also noted that “the maximum yield of a favorably located well might be as much as 500 gal/min” (Welder and McGreevy, 1966, Sheet 3). They also noted that artesian conditions occur in many sandstone lenses in the lower part of the formation, especially in the northwestern Great Divide Basin.

Collentine et al. (1981, Table V-1, p. 44) summarized hydrogeologic characteristics of the Wasatch aquifer throughout the Great Divide and Washakie Basins, including the eastern perimeters of the basins in Carbon County. Reported well yields ranged from 5 to 250 gal/min, but most yields ranged from 30 to 50 gal/min.

A potentiometric surface map of the Wasatch zone of the Wasatch-Fort Union aquifer constructed by Naftz (1996) shows the direction of groundwater flow for the entire aquifer, including the eastern perimeter in western Carbon County. Based on this map, Naftz (1996) reported:

"recharge occurs in upland areas, and outcrop areas adjacent to mountain ranges, and discharge occurs along major streams and rivers of the study area. Springs in the northern part of the Great Divide-Washakie-Sand Wash Basins aquifer system serve as major discharge points; to a lesser degree, springs associated with faulting near the Little Snake River in the southern part of the basin act as discharge points."

Naftz (1996) also examined major-ion geochemistry to identify areas of recharge, discharge, and interaquifer leakage in the Wasatch zone of the Wasatch-Fort Union aquifer. He noted that recharge areas were characterized by small dissolved-solids concentrations, unique calcium and magnesium-to-sodium ratios, and small sodium and fluoride concentrations. Sulfate concentrations generally increased along projected groundwater flowpaths, and water with dissolved-solids concentrations greater than 1,500 mg/L was predominant in sodium and chloride. Examining calcium-to-chloride ratios, he concluded that ratios that exceed the local precipitation ratio are indicative of recharge areas, and ratios less than the local precipitation ratio are indicative of discharge areas.

Powder River Basin (Great Plains)

The Wasatch aquifer in the Powder River Basin consists of the Wasatch Formation (Lewis and Hotchkiss, 1981, and references therein). The Wasatch Formation is composed of fine-to coarse-grained lenticular, discontinuous sandstone beds interbedded with finer-grained sediments with low permeability such as shale, siltstone, claystone, and mudstone (Lewis and Hotchkiss, 1981, and references therein). Coal beds are locally present. The discontinuous lenticular sandstone beds are the geologic materials that primarily yield water to wells and comprise the aquifer in the Powder River Basin (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988; Bartos and Ogle, 2002, and references therein). The Wasatch aquifer overlies and is in hydraulic connection with the underlying Fort Union aquifer throughout the Powder River Basin. The aquifer is widely used for stock and domestic purposes throughout the basin. Hydrogeologic data describing the Wasatch aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

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

Central Wyoming basins (south)

The chemical composition of groundwater in the Wasatch aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (126 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). On the basis of the few characteristics and constituents analyzed for, the quality of water from Wasatch aquifer in the CBS was likely suitable for most uses. No characteristics or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Great Plains

The chemical composition of groundwater in the Wasatch aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were fresh (78 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 228 to 3,200 mg/L, with a median of 516 mg/L.

Concentrations of some characteristics and constituents in water from the Wasatch aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), gross alpha radioactivity (100 percent; MCL of 15 pCi/L), uranium (100 percent; MCL of 30 µg/L), lead (67 percent; MCL (action level) of 15 µg/L), and nitrate plus nitrite (11 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: ammonia (100 percent; WDEQ Class I standard of 0.5 mg/L), iron (67 percent; USEPA SMCL of 300 µg/L), manganese (67 percent; SMCL of 50 µg/L), TDS (56 percent; SMCL of 500 mg/L), sulfate (22 percent; SMCL of 250 mg/L), and pH (10 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent; WDEQ Class II standard of 15 pCi/L), manganese (67 percent; WDEQ Class II standard of 200 µg/L), selenium (33 percent; WDEQ Class II standard of 20 µg/L; supplementary data tables), boron (25 percent; WDEQ Class II standard of 750 µg/L), TDS (22 percent; WDEQ Class II standard of 2,000 mg/L), sulfate (22 percent; WDEQ Class II standard of 200 µg/L), iron (17 percent; WDEQ Class II standard of 5,000 µg/L), and SAR (11 percent; WDEQ Class II standard of 8). Selenium is not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents measured at concentrations greater than livestock-use standards were gross alpha radioactivity (100 percent; WDEQ Class III standard of 15 pCi/L) and pH (10 percent below lower WDEQ Class III limit of 6.5).

7.2.2.17 Coalmont Formation

The physical and chemical characteristics of the Coalmont Formation in the PtRB are described in this section of the report.

Physical characteristics

The Coalmont Formation (**Plate T**) is present in the southern Saratoga Valley (**Plates 1, 2**). Montagne (1991, p. 16) described the unit as "brown coarse-grained arkosic sandstone with a waxy clay matrix." He also stated that the formation can be correlated to the Hanna Formation because of their similar age, structural relations, and similar lithologies. South of Saratoga Valley, the Coalmont Formation is at least 7,000-ft thick in the central part of the North Park Basin of Colorado (Montagne, 1991, p. 17). Little hydrogeologic information is available for the Coalmont Formation in the central Wyoming basins (south) (CBS) because few wells are completed in the unit because of limited areal extent.

Chemical characteristics

The chemical composition of groundwater in the Coalmont Formation in the CBS was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (136 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). On the basis of comparison of concentrations with health-based standards, the environmental water was generally suitable for domestic use. The sample

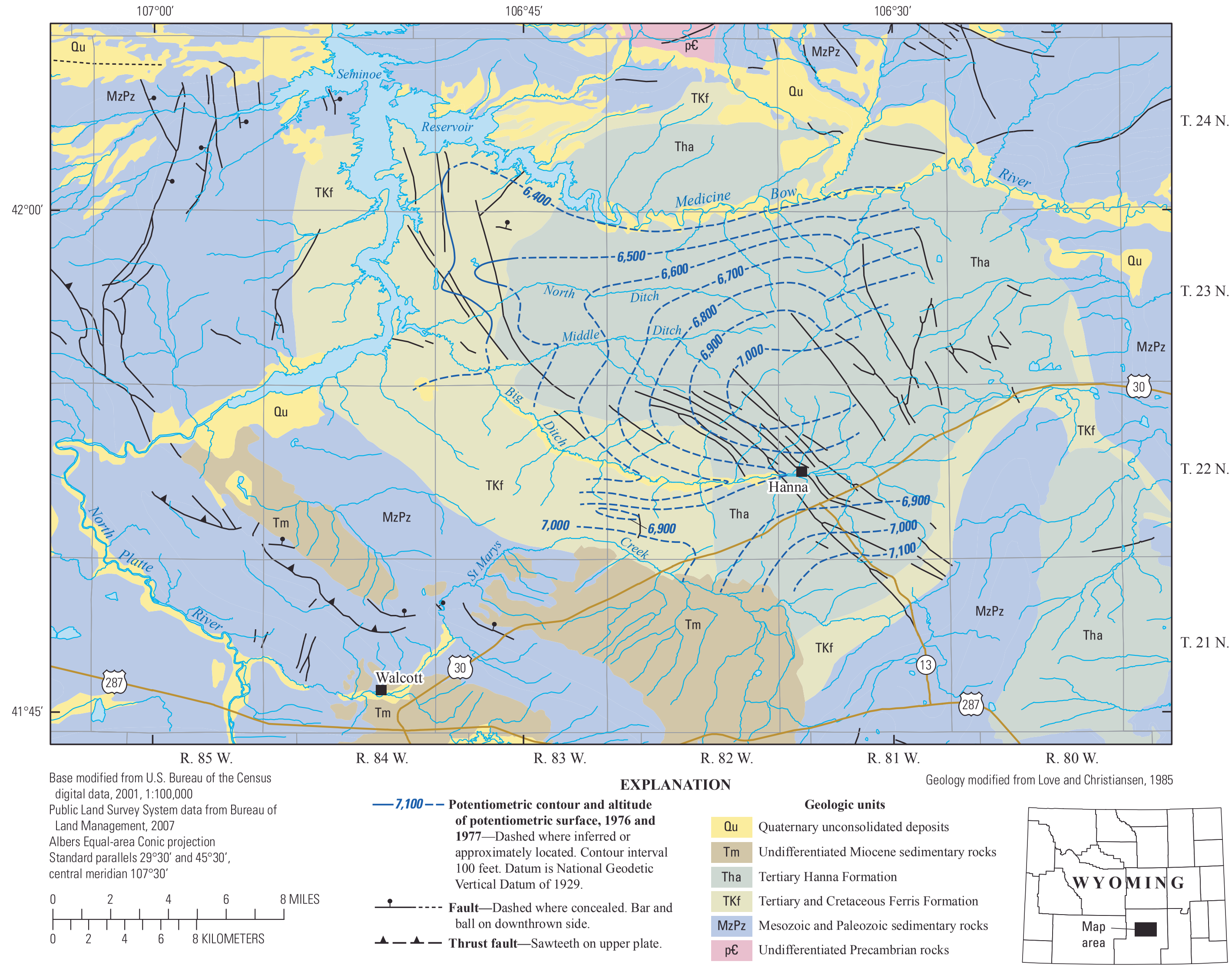


Figure 7-6. Generalized potentiometric surface for the Hanna and Ferris aquifers east of Seminoe Reservoir, Hanna Basin, south-central Wyoming (modified from Davis, 1977, Figure 1).

did exceed the proposed USEPA MCL of 300 pCi/L for radon, but did not exceed the alternative MCL of 4,000 pCi/L for radon. No characteristics or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.2.2.18 Hanna aquifer

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

Physical characteristics

The Hanna aquifer consists of the Paleocene Hanna Formation (**Plate T**) and is present at or near the land surface in the Hanna, Carbon, and Laramie Basins, and the Medicine Bow Mountains (**Plates 1, 2**). The formation was named by Bowen (1918). Hyden et al. (1965) replaced the name Hanna Formation with Dutton Creek Formation in the northern part of the Laramie Basin. Gill et al. (1970) determined that the Dutton Creek Formation was one of the many coarse-grained tongues of the Hanna Formation and reinstated the name Hanna Formation.

The formation consists of alternating beds of sandstone, conglomerate, shale, and coal (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929; Gill et al., 1970; and Lowry et al., 1973). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the fine-grained sandstones are brown in color, whereas the coarse-grained sandstones are buff to grayish white. The sandstones are massive to thin-bedded, with ripple marks and cross-bedding common. They also noted that the formation was highly feldspathic. The dark-gray, yellowish, and carbonaceous shale occur in alternating beds (Bowen, 1918). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the conglomerates and conglomeratic sandstones contain pebbles of chert, granite, quartzite, sandstone, shale from the Mowry Shale, and conglomerate from the Cloverly Formation. Montagne (1991) described the Hanna Formation on Kennaday Peak and Pass Creek Basin as a conglomerate of boulders, cobbles, and pebbles, with a matrix of yellow friable medium-grained sandstone. Dobbin, Bowen, and Hoots (1929) also noted that there were locally massive conglomerates. Love and Christiansen (1985) noted the giant quartzite boulders near the Medicine Bow Mountains. Houston et al. (1968) mapped the feldspathic sandstone, arkose, carbonaceous shale, conglomeratic sandstone, and thick beds of conglomerate as Hanna and Ferris Formations undivided on the flanks of the Medicine Bow Mountains. Love and Christiansen (1985) mapped the unit as the Hanna Formation in the Medicine Bow Mountains. Gill et al. (1970) believe that the formation could be as much as 13,500-ft thick in the deepest part of the Hanna Basin.

Most wells completed in the Hanna aquifer are for stock use or for monitoring purposes near coal mines. Richter (1981a) defined the formation as a “principal aquifer” and grouped the Hanna Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the “Tertiary aquifer.” The USGS also defined the Hanna aquifer as a “principal aquifer” (Whitehead, 1996) and referred to the aquifer as part of the “lower Tertiary aquifers” category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Hanna aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

The Hanna aquifer is composed of individual discontinuous sandstone, conglomerate, and coal beds or lenses (Lowry et al., 1973; Richter, 1981a). Permeability in the sandstones is intergranular, whereas permeability in the coalbeds is from fractures (Lowry et al., 1973; Richter, 1981a). Richter (1981a, Table IV-2, p. 53) reported that yields from “selected pumping wells completed in channel sandstones and conglomerates produce from 1 to 100 gal/min, whereas wells completed in coal seams generally produce less than 20 gal/min.” In addition, Richter (1981a) reported that artesian conditions can occur locally in the Hanna aquifer with flows as large as 20 gal/min.

A generalized potentiometric-surface map constructed by Davis (1977, Figure 1) reproduced herein as **Figure 7-6** shows the direction of groundwater flow for the Hanna and Ferris aquifers between Seminoe Reservoir and the outcrop of the Hanna Formation (area in Township (T.) 22 to T.

24 North (N.), Range (R.) 83 to R. 84 West (W.)). Based on this map, groundwater in the aquifers in this area flows to the north towards the Medicine Bow River, north and south towards Big Ditch, as well as west towards Seminoe Reservoir.

Dewatering of the Hanna aquifer near coal mines in the Hanna Basin was described by Kuhn et al. (1983, p. 70–71). Examination of water levels in wells in and near dewatered mine pits indicated very complex hydrogeologic conditions. Hydraulic connection between individual permeable beds (sandstone and coal) was highly variable and unpredictable. The investigators also suggested that faulting in the area may provide hydraulic connection between individual permeable beds separated by rocks with low vertical permeability.

Chemical characteristics

The chemical composition of groundwater in the Hanna aquifer in the CBS was characterized and the quality evaluated on the basis of environmental water samples from as many as 36 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram C**). TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (49 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram C**; supplementary data tables). TDS concentrations ranged from 28 to 7,500 mg/L, with a median of 1,380 mg/L.

Concentrations of some characteristics and constituents in water from the Hanna aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (in the one filtered sample analyzed for this constituent, the concentration exceeded the WDEQ Class I standard of 0.5 mg/L), beryllium (71 percent of samples analyzed for the constituent; USEPA MCL of 4 μg/L), arsenic (4 percent; MCL of 10 μg/L), and fluoride (3 percent; MCL of 4 mg/L). Beryllium is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (80 percent; USEPA SMCL of 500 mg/L), manganese (68 percent; SMCL of 50 μg/L), sulfate (63 percent; SMCL of 250 mg/L), iron (35 percent; SMCL of 300 μg/L), aluminum (25 percent exceeded lower SMCL limit of 50 μg/L and 5 percent exceeded the upper SMCL limit of 200 μg/L), pH (17 percent above upper SMCL limit of 8.5), and fluoride (12 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were mercury (100 percent; WDEQ Class II standard of 0.05 μg/L; supplementary data tables), sulfate (69 percent; WDEQ Class II standard of 200 mg/L), SAR (50 percent; WDEQ Class II standard of 8), TDS (23 percent; WDEQ Class II standard of 2,000 mg/L), manganese (23 percent; WDEQ Class II standard of 200 μg/L), iron (9 percent; WDEQ Class II standard of 5,000 μg/L), pH (6 percent above upper WDEQ Class II limit of 9.0), chloride (6 percent; WDEQ Class II standard of 100 mg/L), and boron (3 percent; WDEQ Class II standard of 750 μg/L). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents measured at concentrations greater than livestock-use standards were pH (17 percent above upper WDEQ Class III limit of 8.5), chromium (8 percent; WDEQ Class III standard of 50 μg/L), TDS (3 percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (3 percent; WDEQ Class III standard of 3,000 μg/L).

The chemical composition of groundwater in the Hanna aquifer in the CBS also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (4,690 and 5,150 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Hanna aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, sulfate, and iron exceeded aesthetic standards for domestic use (USEPA SMCLs) in both samples. TDS, chloride, and sulfate exceeded agricultural-use standards (WDEQ Class II standards) in both samples. TDS (one sample) and pH (above upper limit in both samples) exceeded State of Wyoming livestock standards (WDEQ Class III standards).

7.2.2.19 Ferris aquifer

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

Physical characteristics

The Ferris aquifer consists of the Ferris Formation (**Plate U**). The Ferris Formation is present at or near the land surface around the Hanna Basin and on the northern margin of the Carbon Basin (**Plates 1, 2**). The Ferris Formation is both Paleocene (Cenozoic) and Late Cretaceous (Mesozoic) in age and was named by Bowen (1918). The formation primarily consists of intertonguing beds of gray, brown, and yellow sandstone, light-colored, dark-gray and carbonaceous shale, and numerous thick beds of coal (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929; Gill et al., 1970; Lowry et al., 1973). Bowen (1918) and Dobbin, Bowen, and Hoots (1929) noted that the basal part of the formation has a zone that is about 1,100-ft thick containing pockets, lenses, and thin beds of conglomerate in a massive buff to yellow sandstone. Dobbin, Bowen, and Hoots (1929) noted that the pebbles usually are less than an inch in diameter and are composed of quartzite, chert, jasper, rhyolite, and porphyry. The lower 300 ft of the formation also includes dark shale (Dobbin, Bowen, and Hoots, 1929). The formation could be as much as 6,500-ft thick.

Most wells completed in the Ferris aquifer are for stock use or for monitoring purposes near coal mines. Richter (1981a) defined the formation as a "principal aquifer" and grouped the Ferris Formation with other formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the "Tertiary aquifer." The USGS also defined the Ferris aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "lower Tertiary aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Ferris aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

The Ferris aquifer is composed of individual discontinuous sandstone, conglomerate, and coal beds or lenses (Lowry et al., 1973; Richter, 1981a). Permeability in the sandstones is intergranular, whereas permeability in the coalbeds is from fractures (Lowry et al., 1973; Richter, 1981a).

A generalized potentiometric-surface map constructed by Davis (1977, Figure 1) reproduced herein as **Figure 7-6** shows the direction of groundwater flow for the Hanna and Ferris aquifers between Seminoe Reservoir and the outcrop of the Hanna Formation (area in T. 22 to T. 24 N., R. 83 to R. 84 W.). Based on this map, groundwater in the aquifer in this area flows to the north towards the Medicine Bow River, north and south towards Big Ditch, as well as west towards Seminoe Reservoir.

A generalized potentiometric-surface map constructed by the Bureau of Land Management (1975, Figure 10, p. 149) reproduced herein as **Figure 7-7** shows the direction of groundwater flow for the Ferris aquifer between Seminoe Reservoir and the outcrop of the Hanna Formation

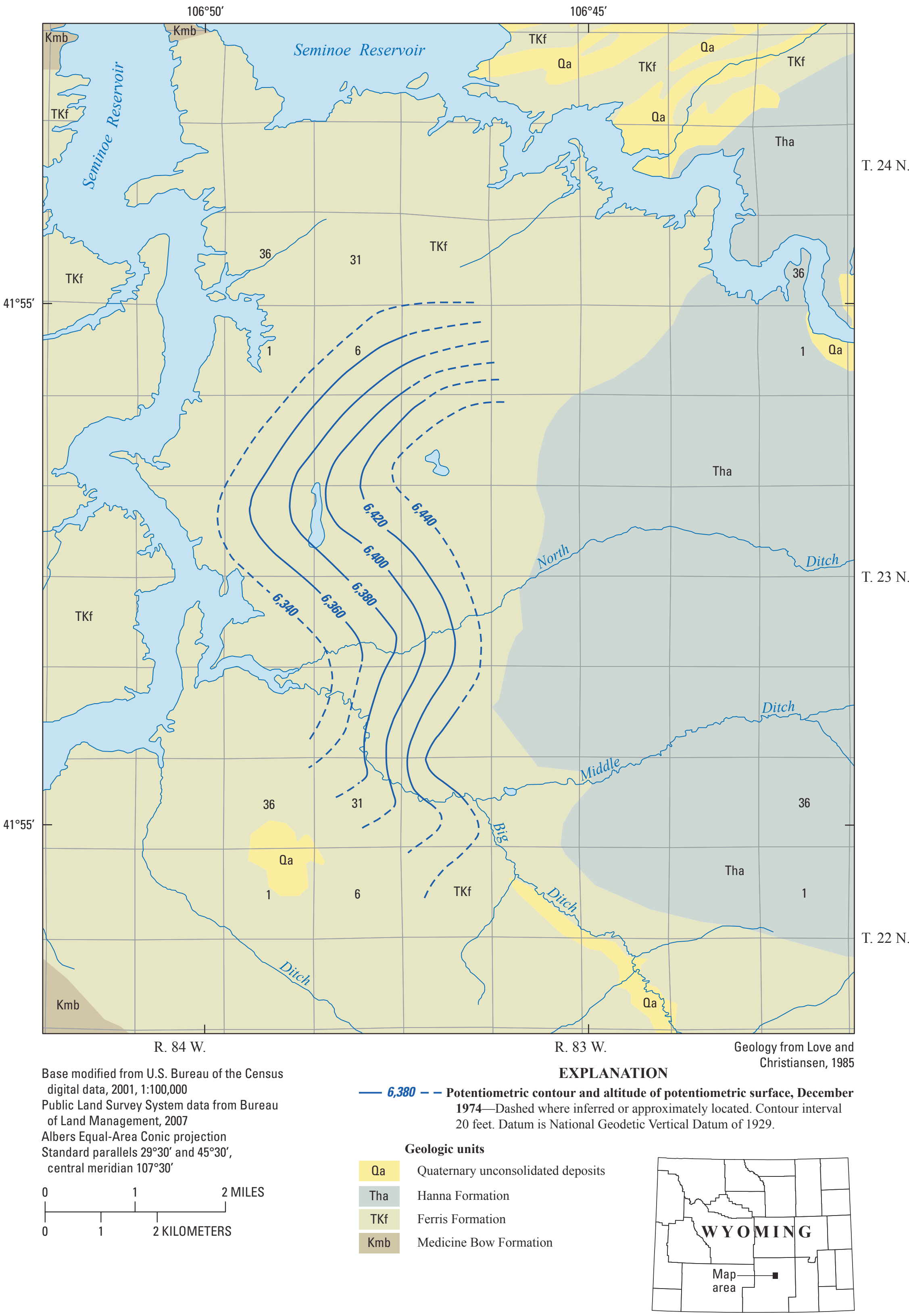


Figure 7-7. Generalized potentiometric-surface for the Ferris aquifer east of Seminoe Reservoir, northwest Hanna Basin, south-central Wyoming (modified from Bureau of Land Management, 1975).

(area in T. 22 to T. 24 N., R. 83 to R. 84 W.). Based on this map, groundwater in the aquifer in this area flows to the west towards Seminoe Reservoir.

Chemical characteristics

The chemical composition of groundwater in the Ferris aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 33 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram D**). TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (55 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram D**; supplementary data tables). TDS concentrations ranged from 614 to 8,240 mg/L, with a median of 2,770 mg/L.

Concentrations of some characteristics and constituents in water from the Ferris aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (100 percent; WDEQ Class I of 0.5 mg/L), beryllium (100 percent of samples analyzed for the constituent; USEPA MCL 4 μg/L), strontium (67 percent; USEPA HAL of 4,000 μg/L), zinc (4 percent; USEPA HAL of 2,000 μg/L); lead (5 percent; MCL (action level) of 15 μg/L), arsenic (4 percent; MCL of 10 μg/L), mercury (4 percent; MCL of 2 μg/L), selenium (4 percent; MCL of 50 μg/L), and zinc (4 percent; HAL of 2,000 μg/L). Mercury is not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L), sulfate (88 percent; SMCL of 250 mg/L), manganese (75 percent; SMCL of 50 μg/L), iron (50 percent; SMCL of 300 μg/L), aluminum (15 percent exceeded lower SMCL limit of 50 μg/L), fluoride (6 percent; SMCL of 2 mg/L), zinc (4 percent; SMCL of 5,000 μg/L), and pH (3 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (94 percent; WDEQ Class II standard of 200 mg/L), TDS (73 percent; WDEQ Class II standard of 2,000 mg/L), manganese (46 percent; WDEQ Class II standard of 200 μg/L), SAR (33 percent; WDEQ Class II standard of 8), vanadium (29 percent; WDEQ Class II standard of 100 μg/L), iron (17 percent; WDEQ Class II standard of 5,000 μg/L), selenium (8 percent; WDEQ Class II standard of 20 μg/L), boron (7 percent; WDEQ Class II standard of 750 μg/L), chloride (6 percent; WDEQ Class II standard of 100 mg/L), and zinc (4 percent; WDEQ Class II standard of 2,000 μg/L). Characteristics and constituents measured at concentrations greater than livestock-use standards were mercury (100 percent; WDEQ Class III standard of 0.05 μg/L), vanadium (29 percent; WDEQ Class III standard of 100 μg/L), TDS (21 percent; WDEQ Class III standard of 5,000 mg/L), sulfate (21 percent; WDEQ Class III standard of 3,000 mg/L), selenium (4 percent; WDEQ Class III standard of 50 μg/L), and pH (3 percent above upper WDEQ Class III limit of 8.5).

7.2.2.20 Fort Union aquifer

The physical and chemical characteristics of the Fort Union aquifer in the PtRB are described in this section of the report. Because of different geologic characteristics and hydrogeologic nomenclature in the two areas where the Fort Union Formation is present in the PtRB (Great Divide Basin and southern Powder River Basin; **Plate 1**), discussion of the Fort Union aquifer is divided into these two geographic areas.

Physical characteristics

Great Divide Basin [central Wyoming basins (south)]

The Fort Union aquifer consists of the Paleocene Fort Union Formation, which is present at or near land surface in the northeast corner of the Great Divide Basin, west of the town of Rawlins (**Plates 1, 2**). Harshman (1972, p. 19) speculated that the Fort Union Formation may be present in the southern part of the Shirley Basin in channels eroded into the Late Cretaceous Steele Shale. The few remnants found are sequences of varicolored soft sandy siltstones that are in part carbonaceous, but no fossils or pollen were recovered for dating. Love and Christiansen (1985) described the Fort Union Formation as "brown to gray sandstone, gray to black shale, and thin coal beds." The formation was deposited during the Paleocene Epoch and Laramide Orogeny. During this time, mountain ranges such as the Sierra Madre and the Granite Mountains were rising at the same time structural basins were subsiding. Love (1970, p. C115) reported that during the Paleocene Epoch, the Great Divide Basin was subsiding, but because the deposition of sediment derived from uplift areas filled the basin at the same rate, the surface of the basin remained at nearly the same altitude throughout the epoch. The same thing was happening in and around other basins depositing the formation during the Paleocene Epoch. The climate was warm and humid, and swamps were common. These swamps eventually would become the numerous coal deposits found in the Fort Union Formation today. Welder and McGreevy (1966, Sheet 3) reported that the thickness of the Fort Union Formation ranges from 700 to about 2,700 ft in the Great Divide and Washakie Basins.

The Fort Union Formation contains an important aquifer in the Great Divide and Washakie Basins. As noted previously, Naftz (1996) and Glover et al. (1998) combined the Wasatch, Battle Spring, and Fort Union Formations into a single hydrogeologic unit defined as the Wasatch-Fort Union aquifer. The USGS also defined the Fort Union aquifer as a "principal aquifer" (Whitehead, 1996) and combines the formation with many others that compose the "Colorado Plateaus aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Welder and McGreevy (1966) and Collentine et al. (1981) described the hydrogeologic characteristics of the Fort Union aquifer throughout the Great Divide and Washakie Basins. Collentine et al. (1981, p. 54) noted that many of the individual discontinuous sandstone beds or lenses are hydraulically isolated, although the investigators noted that sandstone and conglomerate beds in the lower part of the formation in some locations may be hydraulically connected because of fractures. Welder and McGreevy (1966, Sheet 3) reported that well yields for 11 wells ranged from 3 to 300 gal/min and noted "a well penetrating the entire formation where the sandstones are thickest might yield as much as 500 gal/min."

Most published information describing the Fort Union aquifer is from areas immediately west of the PtRB, including the Great Divide, Washakie, and Green River Basins. The reader is referred to previous publications for additional descriptions of the physical and chemical characteristics of the aquifer immediately west of the PtRB (Welder and McGreevy, 1966; Collentine et al., 1981; Taylor et al., 1986; Naftz, 1996; Mason and Miller, 2005; Bartos and Hallberg, 2010; Bartos et al., 2010).

Powder River Basin (Great Plains)

The Fort Union aquifer in the Powder River Basin consists of permeable parts of the Fort Union Formation (Lewis and Hotchkiss, 1981, and references therein). The Fort Union Formation in the Powder River Basin ranges in thickness from about 2,300 to 6,000 feet, and is divided into three members—the Tongue River, Lebo, and Tullock Members (Bartos and Ogle, 2002, and references therein). The Tongue River and Tullock Members consist of fine-to coarse-grained lenticular, discontinuous sandstone beds interbedded with finer-grained sediments with low permeability such as shale, siltstone, claystone, and mudstone (Lewis and Hotchkiss, 1981, and references therein). The Lebo Member consists primarily of shale and mudstone, interbedded with lesser amounts of sandstone, siltstone, and sparse, very thin coal beds. Coal beds are present throughout the formation and comprise some of the most laterally continuous aquifers in the Powder River Basin (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988, and references therein).

The discontinuous lenticular sandstone beds and coal beds, primarily in the Tongue River and Tullock Members, are the actual geologic materials that primarily yield water to wells and comprise the aquifer; both members commonly are considered subaquifers in the Powder River Basin, identified as the Tongue River or Tullock aquifers (Lewis and Hotchkiss, 1981; Bloyd et al., 1986; Martin et al., 1988; Bartos and Ogle, 2002, and references therein). Because the Lebo Member is composed primarily of shale and mudstone, the unit is considered a thick confining unit between the Tongue River and Tullock aquifers. However, sandy zones within the Lebo Member are used locally to supply water for stock or domestic purposes. The Tongue River aquifer underlies and is in hydraulic connection with the overlying Wasatch aquifer throughout the Powder River Basin. Consequently, the combined Tongue River and Wasatch aquifers are commonly referred to as the "Tongue River-Wasatch aquifer" or "Wasatch-Tongue River aquifer" in the Powder River Basin (Lewis and Hotchkiss, 1981). Like the Wasatch aquifer, the Fort Union aquifer is widely used for stock and domestic purposes throughout the Powder River Basin; it is also used for public-supply purposes in parts of the basin. Hydrogeologic data describing the Fort Union aquifer, including well-yield and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

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

Central Wyoming basins (south)

The chemical composition of groundwater in the Fort Union aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (12,400 mg/L) indicated that the water was very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L). Concentrations of some characteristics and constituents in water from the Fort Union in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but aesthetic standards for domestic use and State of Wyoming livestock-use standards were exceeded for TDS (USEPA SMCL of 500 mg/L and WDEQ Class III standard of 5,000 mg/L) and chloride (SMCL of 250 mg/L and WDEQ Class III standard of 2,000 mg/L). TDS, chloride, and sulfate in the produced-water sample exceeded State of Wyoming agricultural-use (WDEQ Class II) standards of 2,000, 100, and 200 mg/L, respectively. The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

Great Plains

The chemical composition of groundwater in the Fort Union aquifer in the GP was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (75 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 417 to 3,030 mg/L, with a median of 567 mg/L.

Concentrations of some characteristics and constituents in water from the Fort Union aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (50 percent), sulfate (25 percent), and pH (20 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (25 percent; WDEQ Class II standard of 8), TDS (25 percent), and sulfate (25 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Fort Union aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (533 mg/L) indicated that the water was fresh. The concentration of one characteristic in produced water from the Fort Union aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS exceeded aesthetic standards for domestic use. No characteristics or constituents exceeded State of Wyoming agricultural and livestock standards.

7.3 Mesozoic Hydrogeologic Units

Mesozoic hydrogeologic units are described in this section of the report. Development of most Mesozoic aquifers in the PtRB has been very limited to date (2013), except in areas where aquifers crop out and are directly exposed at land surface or at shallow depth below younger hydrogeologic units. Most wells in Mesozoic hydrogeologic units have been installed for oil and gas production, often at depths thousands of feet below land surface. Hydraulic properties, great depth, minimal precipitation and recharge, and generally poor water quality prevents extensive groundwater development of aquifers in Mesozoic hydrogeologic units.

7.3.1 Lance aquifer

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

Physical characteristics

The Late Cretaceous Lance Formation, which contains the Lance aquifer, generally is present only at or near the land surface around the mountain-basin margins of the PtRB (**Plates 1, 2**). Throughout most of the PtRB, the Lance aquifer is deeply buried and, consequently, few wells are completed in the unit. In the Goshen Hole area within the Denver-Julesburg Basin, erosion of overlying Tertiary hydrogeologic units has exposed the Lance Formation at land surface (**Plates 1, 2**). The Lance Formation consists of fissile, dark-gray, brown, and carbonaceous shale, siltstone, claystone, and mudstone; interbedded brown to light brown, very fine-to fine-grained, clayey, calcareous sandstone; coal; and lignite (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981, and references therein; James M. Montgomery, Consulting Engineers, Inc., 1990c; TriHydro Corporation, 1996; Lidstone and Associates, Inc., 2003; Dahlgren Consulting, Inc., 2005). The Lance Formation was deposited in a fluvial environment. In the Denver-Julesburg Basin, reported thickness ranges from 0 to 1,500 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 8; Libra et al., 1981, Table IV-1, p. 40; Lidstone and Associates, Inc., 2003; Dahlgren Consulting, Inc., 2005). Berry

(1960) reported a thickness of as much as 4,540 ft in the Rawlins Uplift area.

In the Granite Mountains Uplift and Shirley Basin, the Lance aquifer is overlain by the Fort Union aquifer and confined from below by the Meeteetse confining unit (**Plate J**). The Lance aquifer is overlain by the White River aquifer and confining unit and underlain by the Fox Hills aquifer in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Lance aquifer is overlain by the Fort Union aquifer and underlain by the Fox Hills aquifer (**Plate S**).

The Lance Formation in the Denver-Julesburg Basin was defined as an aquifer by early investigators (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967) (**Plate M**). Libra et al. (1981) defined the Lance Formation as a "minor aquifer" in the Denver-Julesburg Basin (**Plate M**). Because of the absence of a regional confining unit, and hypothesized regional hydraulic connection, Libra et al. (1981) grouped the Lance aquifer and underlying Fox Hills aquifer together into a regional hydrogeologic unit defined as the "Lance-Fox Hills aquifer." Interpretation and use of the regional "Lance-Fox Hills aquifer" definition has been retained in subsequent studies in the Denver-Julesburg Basin (for example, Lidstone and Associates, Inc., 2003c; Dahlgren Consulting, Inc., 2005), and this interpretation tentatively is retained herein (**Plate M**).

The Lance Formation is defined as an aquifer in other parts of the PtRB. Berry (1960) considered the Lance Formation to be a potential aquifer in the Rawlins Uplift area (**Plate S**). Collentine et al. (1981) defined the Lance Formation as a "minor aquifer" and "minor water-bearing unit" in the Great Divide and Washakie Basins and Rawlins Uplift; the investigators also grouped the Late Cretaceous-age Lance Formation and Fox Hills Sandstone with formations of Tertiary age in the Great Divide and Washakie Basins area into a hydrogeologic unit defined as the "Tertiary aquifer system." The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Very fine- to fine-grained water-bearing sandstone beds in the Lance Formation compose the Lance aquifer; the sandstones are interbedded and confined by low-permeability, fine-grained rocks, locally resulting in a series of confined sandstone subaquifers (Libra et al., 1981). Confined conditions predominate, but unconfined conditions are likely in outcrop areas (Rapp et al., 1957; Libra et al., 1981). Where deeply buried, only oil and gas wells are completed in the aquifer. At shallower and economical drilling depths, wells completed in the Lance aquifer in the PtRB are used for stock or domestic purposes, primarily in the Goshen Hole area where the Lance Formation is exposed at land surface (Rapp et al., 1957; Libra et al., 1981). The aquifer is rarely used for public-supply purposes in the PtRB, primarily due to small to moderate well yields, deep burial, poor water quality for intended purposes, or large distances from towns or cities (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981). Wells completed in the aquifer supply water to the town of Rolling Hills in the southern Powder River Basin near Glenrock (James M. Montgomery, Consulting Engineers, Inc., 1990c; TriHydro Corporation, 1996). Hydrogeologic data describing the Lance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

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

Central Wyoming basins (north)

The chemical composition of groundwater in the Lance aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as eight wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were fresh

(86 percent of samples had TDS concentrations less than or equal to 999 mg/L), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 350 to 1,270 mg/L, with a median of 557 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (57 percent were greater than the USEPA SMCL of 500 mg/L) and sulfate (29 percent were greater than the SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (43 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L) and SAR (17 percent; WDEQ Class II standard of 8). No characteristics or constituents exceeded State of Wyoming livestock standards

The chemical composition of groundwater in the Lance aquifer in the CBN also was characterized and the quality evaluated on the basis of six produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,220 to 3,410 mg/L, with a median of 1,710 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), chloride (33 percent; SMCL of 250 mg/L), and pH (20 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), chloride (67 percent; WDEQ Class II standard of 100 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5).

Great Plains

The chemical composition of groundwater in the Lance aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 19 wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram H**). TDS concentrations were variable and indicated that most waters were fresh (87 percent of samples), and remaining waters were slightly saline (**Appendix E7**; **Appendix G5**, **diagram H**; supplementary data tables). TDS concentrations ranged from 264 to 1,950 mg/L, with a median of 699 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: uranium (71 percent of samples analyzed for the constituent; USEPA MCL 30 μg/L) and arsenic (20 percent; MCL of 10 μg/L; supplementary data tables). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: aluminum (the one uncensored value exceeded lower SMCL limit of 50 μg/L and 33 percent exceeded the upper SMCL limit of 200 μg/L), TDS (77 percent), fluoride (36 percent; SMCL of 2 mg/L), pH (32 percent above upper limit), manganese (25 percent; SMCL of 50 μg/L), iron (20 percent; SMCL of 300 μg/L), and sulfate (13 percent). Aluminum, arsenic, and manganese are not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (88 percent), boron (27 percent; WDEQ Class II standard of 750 μg/L), selenium (20 percent; WDEQ Class II standard of 20 μg/L), chloride (13 percent), sulfate (13 percent), and pH (5 percent above upper WDEQ Class II limit of 9.0). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (32 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Lance aquifer in the GP also was characterized and the quality evaluated on the basis of 20 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram A**). TDS concentrations were variable and indicated that most waters were slightly saline (90 percent of samples), and remaining waters were moderately saline (**Appendix F6**; **Appendix H4**, **diagram A**; supplementary data tables). TDS concentrations ranged from 1,010 to 9,620 mg/L, with a median of 1,540 mg/L.

Concentrations of some characteristics and constituents in water from the Lance aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (40 percent), pH (20 percent above upper limit of 8.5 and 5 percent below lower limit of 6.5), and sulfate (10 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (80 percent), TDS (25 percent), and sulfate (20 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: pH (20 percent above upper WDEQ Class III limit of 8.5 and 5 percent below lower limit of 6.5), TDS (10 percent), and chloride (10 percent; WDEQ Class III standard of 2,000 mg/L).

7.3.2 Medicine Bow aquifer

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

Physical characteristics

The Medicine Bow aquifer consists of the Late Cretaceous Medicine Bow Formation (**Plate U**) and is present at or near the land surface around the margins of the Hanna, Carbon, and Laramie Basins

(**Plates 1, 2**). When the formation was named by Bowen (1918), several hundred feet of marine strata were included that have since been assigned to the Fox Hills Sandstone (Dorf, 1938, Gill et al., 1970). Hyden et al. (1965) replaced the name Medicine Bow Formation with Foote Creek Formation in the northern part of the Laramie Basin. Gill et al. (1970) determined that the rocks assigned to the Foote Creek Formation are remnants of the lower coal-bearing part of the Medicine Bow Formation.

The Medicine Bow Formation, as described by Bowen (1918) and Dobbin, Bowen, and Hoots (1929), contains yellow, gray, and carbonaceous shale, coal, and gray to brown sandstone. The investigators also described some massive white sandstone layers in the main body of the formation, and a massive, coarse-grained, friable, and easily eroded sandstone that is interbedded with beds of dark-gray shale at the top of the unit. Gill et al. (1970) noted that the Medicine Bow Formation is a thick continental unit that was deposited after the withdrawal of the Cretaceous sea. The unit is 400- to 6,200-ft thick.

Little hydrogeologic information is available for the Medicine Bow aquifer in the PtRB, and few wells are installed in the aquifer. Regardless, Richter (1981a) defined the formation as a "principal aquifer" and grouped the Medicine Bow Formation with formations of Tertiary age in the Laramie, Shirley, and Hanna Basins into a single hydrogeologic unit defined as the "Tertiary aquifer." Richter (1981a, Table IV-2, p. 53) reported that the formation "locally yields water to springs and shallow wells along outcrops, south flank of Freezeout Mountains." The USGS also defined the Medicine Bow aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Sandstone and coal beds compose the aquifer in the formation. Hydrogeologic data describing the Medicine Bow aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Medicine Bow aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 119 to 1,240 mg/L, with a median of 308 mg/L.

Concentrations of some characteristics and constituents in water from the Medicine Bow aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (in the one filtered sample analyzed for this constituent; USEPA SMCL of 300 μg/L), manganese (in the one sample analyzed for this constituent; USEPA SMCL of 50 μg/L), TDS (33 percent; USEPA SMCL of 500 mg/L), and sulfate (33 percent; USEPA SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Constituents in environmental water samples measured at concentrations greater than agricultural-use standards were manganese (in the one sample analyzed for this constituent; WDEQ Class II standard of 200 μg/L) and sulfate (33 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.3 Fox Hills aquifer

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

Physical characteristics

The Fox Hills aquifer consists of the Late Cretaceous Fox Hills Sandstone (**Plates M, S,**

U), which generally is present only at or near the land surface around the mountain-basin margins of the PtRB (**Plates 1, 2**), although little of it has been mapped in places (for example, Lowry et al., 1973). Several hundred feet of marine strata that had been assigned to the lower Medicine Bow Formation were renamed as the Fox Hills Sandstone (Dorf, 1938; Gill et al., 1970) in parts of the PtRB. It also has been mapped with the Lewis Shale in parts of the PtRB (Lowry et al., 1973; Love and Christiansen, 1985). The Fox Hills Sandstone is pale yellowish-gray, gray, yellow-brown, very fine- to medium-grained sandstone with a few beds of olive-gray to dark-gray sandy shale, thin carbonaceous shale, and thin impure beds of coal (Gill et al., 1970). In south-central Wyoming, the Fox Hills Sandstone is a shallow-marine, barrier-bar, and beach deposit that reflects the transition from the underlying Late Cretaceous marine shales (Lewis or Pierre Shales) to overlying fluvial units (Late Cretaceous Lance and Medicine Bow Formations) (Gill et al., 1970). Reported thickness of the Fox Hills Sandstone in south-central Wyoming ranges from 200 to 700 ft (Gill et al., 1970, and references therein). In the Denver-Julesburg Basin, reported thickness ranges from 0 to 550 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 9; Libra et al., 1981, Table IV-1, p. 40).

The Fox Hills aquifer is overlain by the Lance aquifer and confined from below by the Pierre confining unit in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Fox Hills aquifer is overlain by the Lance aquifer and confined from below by the Lewis confining unit (**Plate S**). The Fox Hills aquifer is overlain by the Medicine Bow aquifer and confined from below by the Lewis confining unit in the Hanna and Laramie Basins (**Plate U**).

Collentine et al. (1981) defined the Lance aquifer as a "minor aquifer" and grouped the Late Cretaceous Lance and Fox Hills Formations with Tertiary formations in the Great Divide and Washakie Basins into a hydrogeologic unit defined as the "Tertiary aquifer system." The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The Fox Hills Sandstone in the Denver-Julesburg Basin was defined as a potential aquifer (Rapp et al., 1957) or an aquifer by early investigators (Morris and Babcock, 1960; Lowry and Crist, 1967) (**Plate M**). Libra et al. (1981) defined the Fox Hills Sandstone as a "minor aquifer" in the Denver-Julesburg Basin (**Plate M**). Because of the absence of a regional confining unit, and hypothesized regional hydraulic connection, Libra et al. (1981) grouped the Fox Hills and overlying Lance aquifers together into a regional hydrogeologic unit defined as the "Lance-Fox Hills aquifer." Interpretation and use of the regional "Lance-Fox Hills aquifer" definition has been retained in subsequent studies in the Denver-Julesburg Basin (for example, Lidstone and Associates, Inc., 2003c; Dahlgren Consulting, Inc., 2005), and this interpretation tentatively is retained herein (**Plate M**).

The Fox Hills Sandstone is defined as an aquifer in other parts of the PtRB. Collentine et al. (1981) defined the Fox Hills Sandstone as a "minor aquifer" in the Great Divide and Washakie Basins and Rawlins Uplift. The USGS defined the aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The permeable parts of the aquifer are composed primarily of very fine- to medium-grained sandstone (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981; Dahlgren Consulting, Inc., 2005). Confined conditions predominate, but unconfined conditions are likely in outcrop areas (Libra et al., 1981). The aquifer is rarely developed in the PtRB, primarily due to deep burial and availability of water from shallower aquifers, poor water quality for intended uses in places, large distances from towns or cities, and little study of hydrogeologic characteristics (Rapp et al., 1957; Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981; Sunrise Engineering and Weston Engineering, Inc., 1998, 2000). Where deeply buried, only oil and gas wells are completed in the aquifer.

Recently, a well was successfully completed in the Fox Hills aquifer to provide water for public-supply purposes to the city of Pine Bluffs in eastern Laramie County in the Denver-Julesburg Basin (Dahlgren Consulting, Inc., 2005). Adequate well yield and water quality sufficient for public-supply purposes and at an economical drilling depth suggests the aquifer has development potential in parts of the PtRB. Hydrogeologic data describing the Fox Hills aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

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

Central Wyoming basins (north)

The chemical composition of groundwater in the Fox Hills aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (83 percent of samples), and remaining waters were fresh (TDS concentrations less than or equal to 999 mg/L (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 943 to 2,050 mg/L, with a median of 1,390 mg/L.

Concentrations of some characteristics and constituents in water from the Fox Hills aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L) and sulfate (100 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent; WDEQ Class II standard 200 mg/L), SAR (67 percent; WDEQ Class II standard of 8), and TDS (17 percent; WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Fox Hills aquifer in the CBN also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (1,180 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Fox Hills aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. Sulfate also exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Fox Hills aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. On the basis of the few characteristics and constituents analyzed for, the quality of water from the Fox Hills aquifer in the PtRB was likely suitable for most uses. No characteristics or constituents in the Fox Hills aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental water sample.

7.3.4 Lewis confining unit

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

Physical characteristics

The Lewis confining unit consists of the Late Cretaceous Lewis Shale (**Plates J, S, T, U**) and is present at or near the land surface between the basins and uplifts of the PtRB (**Plates 1, 2**) and generally is deeply buried elsewhere. In the Hanna and Laramie Basins area (including Carbon Basin), the Lewis Shale is a gradational change from the overlying Fox Hills Sandstone and the underlying Almond Formation of the Mesaverde Group (**Plate U**). The middle sandy unit, called the Dad Member of the Lewis Shale (Gill et al., 1970), is a tongue of the Fox Hills Sandstone. The Lewis Shale is a dark-gray to olive-gray to buff, silty to sandy shale with dark-gray to brown carbonaceous deposits, fossiliferous limestone, siltstone concretions, very fine- to medium-grained, yellowish-gray to brown sandstones, and yellowish-gray non-resistant siltstones (Berry, 1960; Welder and McGreevy, 1966; Gill et al., 1970; Lowry et al., 1973). The Lewis Shale was deposited in a marine environment. The thickness is difficult to determine because of its gradational contact with the Fox Hills Sandstone, and because the two formations are sometimes mapped together and sometimes separately. Gill et al. (1970) measured 2,300 ft of Lewis Shale in the northwestern part of the Hanna Basin and 2,600 ft in the southeastern part of the Carbon Basin.

Because the shale that composes the predominant lithology in the Lewis Shale generally yields small quantities of water, the formation is considered to be a confining unit in the Great Divide and Washakie Basin areas (Berry, 1960; Welder and McGreevy, 1966; Collentine et al., 1981) and in the Laramie, Shirley, and Hanna Basins (Richter, 1981a). These previous investigators also noted that some sandstone lenses in the formation locally will yield small quantities of water to wells. Hydrogeologic data describing the Lewis confining unit, including well-yield and spring-discharge measurements, are summarized on **Plate 3**.

Chemical characteristics

Central Wyoming Basins (south)

The chemical composition of groundwater in the Lewis confining unit in the CBS was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (75 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations in the environmental water samples ranged from 1,340 to 9,180 mg/L, with a median of 1,990 mg/L.

Concentrations of some characteristics and constituents in water from the Lewis confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), strontium (in the one sample analyzed for this constituent; USEPA HAL of 4,000 μg/L) and uranium (in the one sample analyzed for this constituent; USEPA MCL of 30 μg/L).

Concentrations of one characteristic and three constituents exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L), manganese (in the one sample analyzed for this constituent; USEPA SMCL of 50 μg/L), sulfate (100 percent; USEPA SMCL of 250 mg/L), and fluoride (25 percent; USEPA SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), SAR (50 percent; WDEQ Class II standard of 8), and TDS (50 percent; WDEQ Class II standard of 2,000 mg/L). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (25 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (25 percent; WDEQ Class II standard of 3,000 mg/L).

The chemical composition of groundwater in the Lewis confining unit in the CBS also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. TDS concentrations indicated that waters were slightly saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,210 to 2,060 mg/L, with a median of 1,580 mg/L.

Concentrations of some characteristics and constituents in water from the Lewis confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (67 percent; SMCL of 250 mg/L), sulfate (33 percent), and pH (33 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent; WDEQ Class II standard100 mg/L), TDS (33 percent), and sulfate (33 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper WDEQ Class III limit of 8.5).

Great Plains

The chemical composition of groundwater in the Lewis confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (8,450 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Lewis confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards.

7.3.5 Pierre confining unit

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

Physical characteristics

The Pierre confining unit consists of the thick Late Cretaceous Pierre Shale (**Plate M**) and generally is deeply buried in the Denver-Julesburg Basin (**Plates 1, 2**). The Pierre Shale is a dark-gray shale with interbedded thin to moderately thick beds of sandstone; thickness ranges from 0 to 5,700 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 21; Lowry and Crist, 1967, Table 1, p. 9; Libra et al., 1981, Table IV-1, p. 40; Dahlgren Consulting, Inc., 2005). The Pierre Shale was deposited in a marine environment.

Because shale is the predominant lithology in the Pierre Shale, and shale generally yields small quantities of water, the formation generally is considered to be a thick regional confining unit in the Denver-Julesburg Basin (Libra et al., 1981) (**Plate M**). Sandstone lenses in the unit will locally yield small quantities of water to wells in some areas and can be considered "discontinuous minor aquifers" (Libra et al., 1981, Table IV-1, p. 40). Hydrogeologic data describing the Pierre confining unit, including well-yield measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical composition of groundwater in the Pierre confining unit in the GP was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (379 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Pierre confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (pH above upper limit) exceeded aesthetic standards for domestic use (USEPA SMCL of 8.5) and State of Wyoming livestock-use (WDEQ Class III standard of 8.5) and agricultural-use (WDEQ Class II standard of 9.0) standards.

7.3.6 Mesaverde aquifer

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

Physical characteristics

The Mesaverde aquifer consists of the Late Cretaceous Mesaverde Group or Formation (**Plates J, S, T, U**) and is present at or near the land surface between the basins and uplifts of the PtRB (**Plates 1, 2**). In much of the PtRB, the Mesaverde Group or Formation represents a gradational change from the underlying Steele and Cody Shales to the overlying Lewis Shale (**Plates J, S, T, U**). In parts of the PtRB, much of the Mesaverde Formation was eroded prior to and following the deposition of the Teapot Sandstone Member (Reynolds, 1966, 1967). Reynolds (1966, 1967) indicated that the Mesaverde Formation was completely eroded from some areas in the PtRB. In other areas, rocks of the Mesaverde Group, as assigned by Gill et al. (1970), consist of the Almond Formation, Pine Ridge Sandstone (Teapot Sandstone Member equivalent), Allen Ridge Formation, Rock River Formation, and Haystack Mountains Formation (Love et al., 1993; **Plate U**). Previous studies (Bowen, 1918; Dobbin, Bowen, and Hoots, 1929) referred to an upper sequence (sandstone, shale, carbonaceous shale, and coal), a middle sequence (sandstone, carbonaceous shale, and coal of fresh-and brackish-water origin), and a lower sequence (marine sandstone and shale).

The undifferentiated Mesaverde Formation present in some areas is described as light gray to brown, very fine-to medium-grained sandstone interbedded with gray to dark-gray shale, siltstone, lenses of carbonaceous shale, thin lenses of lignite, and thick sections of coal (Berry, 1960; Reynolds, 1966; Welder and McGreevy, 1966). Reynolds (1966, 1967) described the Teapot Sandstone Member as a lower light-gray to white sandstone and an upper sequence of reddish-brown to white weathered carbonaceous siltstone and sandstone beds. Reynolds (1966) indicated that the Mesaverde Formation is of littoral, shallow marine, brackish, and non-marine origins. Berry (1960) and Welder and McGreevy (1966) gave a maximum thickness of 2,800 ft.

The Almond Formation of the Mesaverde Group intertongues with the overlying Lewis Shale (**Plates S, U**) (Gill et al., 1970; Love et al., 1993). The Almond Coal Group was described by Schultz (1909) and elevated to formation rank by Sears (1926). The Almond Formation is described as interbedded sandstone, siltstone, shale, and coal (Welder and McGreevy, 1966; Gill et al., 1970). The very fine-grained sandstone is white to pale yellowish-gray to dusky yellow, and it weathers to brown (Schultz, 1909; Gill et al., 1970). The shales are dark-gray to olive-gray or brownish-gray to brownish-black and carbonaceous to coaly (Schultz, 1909; Gill et al., 1970). Gill et al. (1970) indicated that the lower part is fluvial sandstone, shale, and coal, whereas the upper part is shallow-water marine sandstone, lagoonal or brackish-water rocks, and marine shale (tongues of Lewis Shale). The Almond Formation ranges from 0- to 600-ft thick.

The Pine Ridge Sandstone of the Mesaverde Group (**Plates S, U**) is a white to pale yellowish-gray to light-gray, fine- to medium-grained, non-marine sandstone (Dobbin, Hoots, et al., 1929; Gill et al., 1970). Gill et al. (1970) indicate that this formation is equivalent to the Teapot Sandstone Member of the Mesaverde Formation. The Pine Ridge Sandstone also contains beds of light-gray carbonaceous shale, gray sandy shale, and beds of impure coal (Dobbin, Hoots, et al., 1929; Gill et al., 1970). Gill et al. (1970) noted that this is a fluvial deposit during the eastward regressive tongue of the Mesaverde Group, with a thickness of 60 to 450 ft.

The Allen Ridge Formation of the Mesaverde Group intertongues with the Rock River Formation in the northwestern Laramie Basin (**Plate U**). It consists of an upper unit of reddish-brown carbonaceous shale, shallow-water marine sandstone, and dark brownish-gray ironstone-bearing shale (Bergstrom, 1959; Gill et al., 1970). The middle unit consists of fossiliferous shale, siltstone, and sandstone (Bergstrom, 1959; Gill et al., 1970). The lower unit consists of brown to rusty-brown fluvial sandstone and shale that contains many beds of carbonaceous shale, very little coal, and numerous ironstone concretions (Bergstrom, 1959; Gill et al., 1970). Gill et al. (1970) noted that the unit is entirely non-marine in the Great Divide and Washakie Basins. They also indicated the formation has a thickness of 0 to 1,275 ft.

Darton and Siebenthal (1909) first described the rocks of the Rock River Formation of the Mesaverde Group (**Plate U**) in the northern Laramie Basin, but the formation was named by Gill et al. (1970). It grades westerly into the Allen Ridge Formation and easterly into the Pierre Shale (Gill et al., 1970). Gill et al. (1970) described it as light-gray to light-brown, very fine-to fine-grained sandstone that is locally shaly, with a few beds of soft sandy shale. They noted that this shallow-water marine unit has a maximum thickness of about 1,565 ft.

The Haystack Mountains Formation is the oldest unit of the Mesaverde Group and has a gradational contact with the underlying Steele Shale (**Plates S, U**). Gill et al. (1970) named three sandstone members of the unit: Hatfield (in upper part), O'Brien Spring (in middle part), and Tapers Ranch (at base) Sandstone Members. They described the unit as pale yellowish-gray, very fine- to fine-grained sandstone interbedded with gray to brownish-gray shale and sandy shale containing fossiliferous concretions of ironstone, limestone, or argillaceous sandstone. The sandstone is a near-shore to off-shore marine deposit, whereas the shales are deep marine deposits. Gill et al. (1970) reported a thickness of 850 to 2,550 ft.

In the Granite Mountains Uplift, Shirley Basin, and the Rawlins Uplift, the Mesaverde aquifer is confined from above by the Lewis confining unit and confined from below by either the Cody or Steele confining units (**Plates J, S**). The Mesaverde aquifer is overlain by the Wind River aquifer and confined from below by the Steele confining unit in the Hartville Uplift and Laramie Mountains (**Plate K**). The Mesaverde aquifer is overlain by the Lewis confining unit and confined from below by the Steele confining unit in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

The Mesaverde Group or Formation is defined as an aquifer by all previous investigators, even though hydrogeologic characteristics of the individual formations (when elevated to group rank) composing the unit can vary. Collentine et al. (1981) defined the formation as a "major aquifer" in the Great Divide and Washakie Basins (**Plate S**), and Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plates J, U**). Collentine et al. (1981) summarized hydraulic properties for the Mesaverde aquifer throughout the Great Divide and Washakie Basins. The USGS defined the Mesaverde aquifer as a "principal aquifer" (Whitehead, 1996) and referred to the formation as part of the "Upper Cretaceous aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013). Hydrogeologic data describing the Mesaverde aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Excluding oil and gas production, few wells are installed in the Mesaverde aquifer. Sandstone beds within the aquifer have potential for development for stock, domestic, or limited public-supply use, although water quality determined during this study would preclude many uses without treatment. Domestic or stock wells generally are completed only in areas where the aquifer crops out. Development of the aquifer has been very limited because of the availability of shallower and better sources of groundwater, availability of surface water in areas where the aquifer crops out, and towns or cities are not located close to the aquifer (Richter, 1981a). Confined conditions predominate, but unconfined (water-table conditions) are likely in Mesaverde aquifer outcrop areas.

In the Rawlins Uplift area, Berry (1960) noted limited potential for development of the Mesaverde aquifer. He noted that much of the Mesaverde Formation was unsaturated in the area, although the formation was saturated downdip in some locations and that "the sandstone beds probably will yield water to wells along the western flank of the Rawlins Uplift" (Berry, 1960, p. 22). He also noted that the area in which wells could be located in the saturated zone of the formation in the Rawlins Uplift area was small because of the steep dip of the beds in the area.

Welder and McGreevy (1966) reported that the groundwater development possibilities of the Mesaverde aquifer in the Great Divide and Washakie Basins were largely unknown. They also noted that groundwater development possibilities in the Almond Formation of the Mesaverde Group "are largely unknown but probably fair" and noted that yields of 20 to 100 gal/min were possible (Welder and McGreevy, 1966, Sheet 3).

Richter (1981a) evaluated the hydrogeology of the Mesaverde aquifer in the Laramie, Shirley, and Hanna Basin areas. In parts of these areas, he reported that the Mesaverde Formation contained a good aquifer that was laterally continuous and semiconfined. The aquifer is elevated, dissected, and unsaturated in the northwestern part of the Laramie Basin, so development potential in this area was reported to be poor. In the Hanna and Shirley Basins, the Mesaverde aquifer is structurally depressed, laterally continuous, and semiconfined; development potential for the aquifer is considered "good" along the margins of these basins because of saturation and presence of numerous springs. Along the flanks of Elk Mountain, Richter (1981a) speculated that groundwater development potential in this area was "excellent" because of faulting and fracturing in the area. The investigator reported that intergranular and fracture permeabilities were "large" and that yields from wells commonly ranged from 1 to 33 gal/min. Faulted and fractured zones within the Mesaverde aquifer were much more productive than undeformed areas. The Pine Ridge Sandstone was reported to be the most productive unit within the Mesaverde aquifer; reported yields ranged from 1 to 50 gal/min, and springs discharged 1 to 5 gal/min.

Recharge to the Mesaverde aquifer is primarily by infiltration of precipitation and streamflow on outcrops (Whitcomb and Lowry, 1968; Richter, 1981a, b). Richter (1981b, p. 80) noted recharge occurs to the Mesaverde aquifer in outcrop areas in the Casper Arch area. Where buried, interformational flow also may contribute to aquifer recharge (Richter, 1981a).

Discharge from the Mesaverde aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Whitcomb and Lowry, 1968; Richter, 1981a, b). In the northwestern part of the Laramie Basin, springs discharge from the Mesaverde aquifer and "generally drain elevated and highly dissected outcrops" (Richter, 1981a, p. 68). The primary anthropogenic source of discharge is oil and gas wells.

Collentine et al. (1981, p. 61) constructed a generalized potentiometric map for the Mesaverde aquifer, including the eastern margin of the Great Divide and Washakie Basins. The map shows that groundwater flow in the area generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Chemical characteristics

The chemical characteristics of the Mesaverde aquifer (composed of groundwater-quality samples from the undivided Mesaverde Formation and different formations or members of the Mesaverde Group or Formation) are described in this section the report. In addition, the chemical characteristics of produced-water samples from two members of the Mesaverde Formation [Teapot Sandstone (equivalent to Pine Ridge Sandstone) and Parkman Sandstone Members of the Mesaverde Formation] identified by petroleum producers are described.

Central Wyoming basins (south)

The chemical composition of groundwater in the Mesaverde aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as 17 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, **diagram E**). TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (53 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; **Appendix G2**, **diagram E**; supplementary data tables). TDS concentrations ranged from 181 to 5,200 mg/L, with a median of 974 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (67 percent of samples analyzed for the constituent exceeded proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), strontium (17 percent; USEPA HAL of 4,000 μg/L), ammonia (17 percent; WDEQ Class I standard of 0.5 mg/L), and zinc (14 percent; HAL of 2,000 μg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (88 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (76 percent; SMCL of 250 mg/L), iron (71 percent; SMCL of 300 μg/L), manganese (43 percent; SMCL of 50 μg/L), fluoride (12 percent; SMCL of 2 mg/L), and pH (8 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (76 percent of samples analyzed for the constituent; WDEQ Class II standard of 200 mg/L), manganese (29 percent; WDEQ Class II standard of 200 μg/L), SAR (24 percent; WDEQ Class II standard of 8), TDS (18 percent; WDEQ Class II standard of 2,000 mg/L), iron (14 percent; WDEQ Class II standard of 5,000 μg/L), and zinc (14 percent; WDEQ Class II standard of 2,000 μg/L). Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: pH (8 percent below lower WDEQ Class III limit of 6.5), TDS (6 percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (6 percent; WDEQ Class III standard of 3,000 mg/L).

The chemical composition of groundwater in the Mesaverde aquifer in the CBS also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were slightly saline (78 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,090 to 11,200 mg/L, with a median of 1,710 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (67 percent), chloride (33 percent; SMCL of 250 mg/L), sulfate (25 percent), and pH (22 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (44 percent; WDEQ Class II standard of 100 mg/L), iron (33 percent), sulfate (25 percent), and TDS (44 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: pH (22 percent above upper WDEQ Class III limit of 8.5), TDS (22 percent), and chloride (11 percent; WDEQ Class III limit of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 11 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Mesaverde aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from two wells (one sample was analyzed for major ions, and the other sample was analyzed for other constituents). Individual constituent concentrations for this sample are listed in **Appendix E6**. One TDS concentration (1,790 mg/L) indicated that waters were slightly saline (**Appendix E6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for the constituent exceeded proposed MCL, but did not exceed alternative MCL). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use in one sample: TDS, fluoride, and sulfate.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards in one sample were SAR, boron (WDEQ Class II standard of 750 μg/L), and sulfate. No characteristics or constituents exceeded State of Wyoming livestock standards

The chemical composition of groundwater in the Mesaverde aquifer in the CBN also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were moderately saline (67 percent of samples), and remaining waters were slightly saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 2,880 to 4,190 mg/L, with a median of 3,210 mg/L.

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), sulfate (100 percent), chloride (67 percent), and pH (33 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards in all three samples were TDS, chloride, and sulfate. Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

Great Plains

The chemical composition of groundwater in the Mesaverde aquifer in the GP was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for these samples are listed in **Appendix F6**. The TDS concentrations (5,010 and 15,400 mg/L) indicated that waters were moderately to very saline (**Appendix F6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mesaverde aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards: TDS and chloride in both samples, and sulfate in one sample. Concentrations of one characteristic and one constituent was measured at greater than State of Wyoming livestock-use standards: TDS (in both samples), and chloride (in one sample). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in one of the produced-water samples.

7.3.6.1 Teapot Sandstone Member of Mesaverde Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Teapot Sandstone Member of Mesaverde Formation in the CBN was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations indicated that waters were moderately saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,240 to 1,730 mg/L, with a median of 1,420 mg/L.

Concentrations of some characteristics and constituents in water from the Teapot Sandstone Member of Mesaverde Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent) and sulfate (33 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Two constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (67 percent) and chloride (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Teapot Sandstone Member of Mesaverde Formation in the GP was characterized and the quality evaluated on the basis of 17 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram B**). TDS concentrations were variable and indicated that most waters were very saline (88 percent of samples), and remaining waters ranged from slightly to moderately saline (**Appendix F6**; **Appendix H4**, **diagram B**; supplementary data tables). TDS concentrations ranged from 2,880 to 17,200 mg/L, with a median of 14,400 mg/L.

Concentrations of some characteristics and constituents in water from the Teapot Sandstone Member of Mesaverde Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (100 percent), sulfate (8 percent), and iron (one sample analyzed for this constituent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent), chloride (100 percent), and sulfate (15 percent). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (94 percent) and chloride (94 percent). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 88 percent of produced-water samples.

7.3.6.2 Parkman Sandstone Member of Mesaverde Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Parkman Sandstone Member of the Mesaverde Formation in the CBN was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples), and remaining waters were moderately saline (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 1,370 to 4,780 mg/L, with a median of 1,660 mg/L.

Concentrations of some characteristics and constituents in water from the Parkman Sandstone Member of Mesaverde Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), pH (33 percent above upper limit), chloride (25 percent), and sulfate (25 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (25 percent), chloride (25 percent), and sulfate (25 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

Great Plains

The chemical composition of groundwater in the Parkman Sandstone Member of Mesaverde Formation in the GP was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**. TDS concentrations were variable and indicated that waters ranged from moderately saline to very saline (**Appendix F6**; supplementary data tables). TDS concentrations ranged from 3,140 to 17,400 mg/L, with a median of 11,000 mg/L.

Concentrations of some characteristics and constituents in water from the Parkman Sandstone Member of Mesaverde Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (100 percent), iron (in the one sample analyzed for this constituent), and pH (50 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent), chloride (100 percent), iron (in the one sample analyzed for this constituent), and sulfate (33 percent). Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: TDS (75 percent), chloride (75 percent), and pH (50 percent above upper limit). State of Wyoming Class IV TDS standards were exceeded in 50 percent of produced-water samples.

7.3.7 Cody confining unit

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

Physical characteristics

The Cody confining unit consists of the Late Cretaceous Cody Shale (**Plates J, S**). The Cody Shale is equivalent to the Steele Shale and Niobrara Formation (**Plates J, S**) and is present in areas where the Niobrara Formation is poorly developed or missing (**Plates 1, 2**) (Weitz and Love, 1952; Reynolds, 1966; Gill et al., 1970). The Cody Shale is described as gray soft shale with thin gray sandstone and siltstone beds (Weitz and Love, 1952; Weimer and Guyton, 1961; Welder and McGreevy, 1966). Weitz and Love (1952) noted a smoky-gray limy shale at the base of the unit. There is a minor amount of bentonite in the unit (Weimer and Guyton, 1961; Welder and McGreevy, 1966). Weimer and Guyton (1961) indicated that this marine shale is as much as 4,500-ft thick. Parts of the Cody Shale are very important oil and gas reservoirs.

Because shale is the predominant lithology in the regionally extensive Cody Shale, and shale generally yields small quantities of water, the formation is considered to be a thick regional confining unit between the overlying Mesaverde aquifer and the underlying Frontier aquifer where present in the PtRB (**Plates J, S**) (Berry, 1960; Welder and McGreevy, 1966; Collentine et al., 1981; Richter, 1981a). The USGS defined the formation as a “confining unit” (Whitehead, 1996). These previous investigators also noted that some sandstone lenses are locally present in the formation and will yield small quantities of water to wells, although the water likely would be highly mineralized. Hydrogeologic data describing the Cody confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

The chemical characteristics of the Cody confining unit (composed of groundwater-quality samples from the undivided Cody Shale and different members of the Cody Shale) are described in this section the report. In addition, the chemical characteristics of produced-water samples from one member of the Cody Shale (Shannon Sandstone Member of the Cody Shale) identified by petroleum producers are described.

Central Wyoming basins (south)

The chemical composition of groundwater in the Cody confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (5,110 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; USEPA SMCL of 500 mg/L and WDEQ Class III standard of 5,000 mg/L) and one constituent (sulfate; SMCL of 250 mg/L and WDEQ Class III standard of 3,000 mg/L) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (SAR and TDS; WDEQ Class II standards of 8 and 2,000 mg/L, respectively) and one constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards.

The chemical composition of groundwater in the Cody confining unit in the CBS also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (1,550 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS exceeded aesthetic standards for domestic use. Chloride exceeded State of Wyoming agricultural standards (WDEQ Class II standard of 100 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Cody confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (7,760 mg/L) indicated that the water was moderately saline (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Cody confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use, but concentrations of two constituents exceeded health-based standards: arsenic and selenium (USEPA MCLs of 10 and 50 μg/L, respectively). One characteristic (TDS) and two constituents (selenium, which has a WDEQ Class III standard of 50 μg/L, and sulfate) exceeded aesthetic standards for domestic use and State of Wyoming livestock standards. Two characteristics (SAR and TDS) and four constituents (boron, which has a WDEQ Class II standard of 750 μg/L, chloride, selenium, which has a WDEQ Class II standard of 20 μg/L, and sulfate) exceeded the State of Wyoming agricultural-use standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Cody confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as 34 wells. Summary statistics calculated for available constituents are listed in **Appendix E6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G4**, **diagram D**). TDS concentrations were variable and indicated that most waters were moderately saline (38 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to briny (TDC concentrations greater than 34,999 mg/L) (**Appendix E6**; **Appendix G4**, **diagram D**; supplementary data tables). TDS concentrations ranged from 422 to 98,500 mg/L, with a median of 3,630 mg/L.

Concentrations of some characteristics and constituents in water from the Cody confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: strontium (in the one sample analyzed for this constituent, USEPA HAL of 4,000 μg/L), selenium (70 percent), nitrate plus nitrite (57 percent; MCL of 10 mg/L), molybdenum (10 percent; HAL of 40 μg/L), fluoride (8 percent; MCL of 4 mg/L), and cadmium 5 percent; MCL of 5 μg/L). Cadmium is not included in **Appendix E6** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: manganese (in the one sample analyzed for this constituent; SMCL of 50 μg/L), TDS (94 percent), sulfate (94 percent), fluoride (25 percent; SMCL of 2 mg/L), and chloride (16 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were lithium (in the one sample analyzed for this constituent; WDEQ Class II standard of 2,500 μg/L), sulfate (94 percent), TDS (74 percent), selenium (73 percent), SAR (44 percent), chloride (44 percent), boron (39 percent), and cadmium (5 percent; WDEQ Class II standard of 5 μg/L; supplementary data tables). Cadmium is not included in **Appendix E6** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: selenium (70 percent), sulfate (38 percent), TDS (32 percent), and nitrate plus nitrite (19 percent; WDEQ Class III standard of 100 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 19 percent of environmental water samples.

7.3.7.1 Shannon Sandstone Member of the Cody Shale

Central Wyoming basins (south)

The chemical composition of groundwater in the Shannon Sandstone Member of the Cody Shale in the CBS was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (7,570 and 17,500 mg/L) indicated that waters ranged from moderately saline ((TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Shannon Sandstone Member of the Cody Shale in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use and State of Wyoming agricultural- and livestock-use standards: TDS and chloride in both samples. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Shannon Sandstone Member of the Cody Shale in the CBN was characterized and the quality evaluated on the basis of 25 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram A**). TDS concentrations were variable and indicated that most waters were very saline (64 percent of samples), and remaining waters ranged from slightly saline to briny (**Appendix F5**; **Appendix H3**, **diagram A;** supplementary data tables). TDS concentrations ranged from 1,280 to 48,000 mg/L, with a median of 15,700 mg/L.

Concentrations of some characteristics and constituents in water from the Shannon Sandstone Member of the Cody Shale in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), sulfate (25 percent), and pH (7 percent below lower SMCL limit of 6.5 and 7 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent of samples analyzed for the constituent), TDS (96 percent), and sulfate (33 percent). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (92 percent), chloride (88 percent; WDEQ Class III standard of 2,000 mg/L), and pH (7 percent below lower WDEQ Class III limit of 6.5 and 7 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 72 percent of produced-water samples.

7.3.8 Steele confining unit

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

Physical characteristics

The Steele confining unit consists of the Late Cretaceous Steele Shale (**Plates J, K, S, T, U**) and is present throughout much of the PtRB, except in some areas where it cannot be differentiated from the underlying Niobrara Formation and both units are referred to as the Cody Shale. The Steele Shale has gradational contacts with the overlying Mesaverde Formation as well as with the underlying Niobrara Formation (**Plates J, K, S, T, U**). It is a dark-gray shale with some layers of limestone, sandstone, siltstone, and bentonite (Dobbin, Bowen, and Hoots, 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972; Gill et al., 1970; Naftz and Barclay, 1991). Sandstone is more common in the upper part of the formation. The formation was deposited in a marine environment. The thickness varies from 2,300 to 5,000 ft, depending on how the upper and lower gradational contacts are chosen (Gill et al., 1970).

Because shale is the predominant lithology in the Steele Shale, and shale generally yields small quantities of water, the formation generally is considered to be a regional confining unit (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) or a regional leaky confining unit (Richter, 1981a). These previous investigators also noted that some sandstone lenses are present in the confining unit and will locally yield small quantities of water to wells, although water likely would be highly mineralized. Within the Steele Shale, Richter (1981a, p. 73) considered the Shannon Sandstone Member to be a "reliable, but undeveloped, source of groundwater." The investigator reported that water in the unit was under confined conditions, and artesian flows ranged from 1 to 25 gal/min at selected petroleum wells. Hydrogeologic data describing the Steele confining unit, including well-yield and other hydraulic properties, are summarized on **Plate 3.**

Central Wyoming basins (south)

The chemical composition of groundwater in the Steele confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as eight wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (43 percent of samples), and remaining waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 175 to 17,900 mg/L, with a median of 3,420 mg/L.

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: ammonia (75 percent; WDEQ Class I of 0.5 mg/L), strontium (67 percent; USEPA HAL of 4,000 μg/L), antimony (33 percent; USEPA MCL of 6 μg/L), arsenic (33 percent; MCL of 10 μg/L), molybdenum (33 percent; HAL of 40 μg/L), nickel (33 percent; HAL of 100μg/L), radon (33 percent of samples analyzed for the constituent exceeded proposed MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L), selenium (33 percent; MCL of 50 μg/L), uranium (33 percent; MCL of 30 μg/L) nitrate plus nitrite (25 percent; MCL of 10 mg/L), and nitrate (12 percent; MCL of 10 μg/L). Nickel and selenium are not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (71 percent; SMCL of 500 mg/L), sulfate (71 percent; SMCL of 250 mg/L), manganese (67 percent; SMCL of 50 μg/L), iron (33 percent; SMCL of 300 μg/L), and chloride (29 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (71 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), manganese (67 percent; WDEQ Class II standard of 200 μg/L), SAR (57 percent; WDEQ Class II standard of 8), TDS (57 percent; WDEQ Class II standard of 2,000), cobalt (33 percent; WDEQ Class II standard of 50 μg/L), lithium (33 percent; WDEQ Class II standard of 2,500 μg/L), nickel (33 percent; WDEQ Class II standard of 200 μg/L; supplementary data tables), boron (29 percent; WDEQ Class II standard of 750 μg/L), chloride (29 percent; WDEQ Class II standard of 100 mg/L), and selenium (33 percent; WDEQ Class II standard of 20 μg/L). Nickel and selenium are not included in **Appendix E2** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents were measured at greater than State of Wyoming livestock-use standards: selenium (33 percent; WDEQ Class III standard of 50 μg/L), TDS (29 percent; WDEQ Class III standard of 5,000 mg/L), and sulfate (29 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 14 percent of environmental water samples.

The chemical composition of groundwater in the Steele confining unit in the CBS also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (1,910 and 11,800 mg/L) indicated that waters ranged from moderately to very saline (**Appendix F2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and two constituents exceeded aesthetic standards for domestic use: TDS in both samples and chloride and sulfate in one sample. TDS, chloride and sulfate exceeded State of Wyoming agricultural-use standards in one sample. TDS and chloride (WDEQ Class III standard of 2,000 mg/L) exceeded State of Wyoming livestock-use standards in one sample. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Steele confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Individual constituent concentrations for this sample are listed in **Appendix E6**. TDS concentrations were variable and indicated that waters ranged from fresh to moderately saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 511 to 3,160 mg/L, with a median of 1,530 mg/L.

Concentrations of some characteristics and constituents in water from the Steele confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent) and sulfate (67 percent).

Concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent), sulfate (67 percent), boron (33 percent), and TDS (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.9 Niobrara confining unit

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

Physical characteristics

The Niobrara confining unit consists of the Late Cretaceous Niobrara Formation (**Plates J, K, M, S, T, U**) and generally is deeply buried throughout most areas of the PtRB. In some areas, the Niobrara Formation cannot be differentiated from the overlying Steele Shale and both units are referred to as the Cody Shale (Love et al., 1993). The Niobrara Formation is a dark-gray calcareous shale with some light-colored layers of limestone, chalk, and sandstone (Dobbin, Bowen, and Hoots, 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972). There are some thin layers of white crystalline calcite (Dobbin, Bowen, and Hoots, 1929). Hale (1961) noted that the Niobrara Formation is lighter in color and more calcareous than the overlying Steele Shale. The formation was deposited in a marine environment. Reported thickness in the PtRB ranges from 0 to

1,475 ft (Dobbin, Bowen, and Hoots, 1929; Rapp et al., 1957; Berry, 1960; Morris and Babcock, 1960; Lowry and Crist, 1967; Harshman, 1968, 1972; Richter, 1981a).

Similar to the previously described Lewis, Cody, and Steele Shales, shale is the predominant lithology in the Niobrara Formation and the formation generally is considered to be a regional leaky confining unit or confining unit (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Libra et al., 1981; HydroGeo, Inc., 2003) (**Plates J, K, M, S, T, U**). The USGS defined the formation as a "confining unit" (Whitehead, 1996). These previous investigators also noted that sandstone lenses are present in the formation and will yield small quantities of water to wells, although water is likely highly mineralized. Hydrogeologic information describing the Niobrara confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate 3**.

Sweetwater Arch

The chemical composition of groundwater in the Niobrara confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (8,580 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards (TDS: USEPA SMCL of 500 mg/L, WDEQ Class II standard of 2,000 mg/L, and WDEQ Class III standard of 5,000 mg/L; chloride: SMCL of 250 mg/L, WDEQ Class II standard of 100 mg/L, and WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Niobrara confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that waters ranged from fresh (TDS concentrations less than or equal to 999 mg/L) to slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 679 to 2,950 mg/L, with a median of 1,510 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), ammonia (50 percent; WDEQ Class I of 0.5 mg/L), and nitrate (20 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent) and sulfate (50 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were boron (67 percent of samples analyzed for the constituent; WDEQ Class II standard 750 μg/L), SAR (50 percent; WDEQ

Class II standard of 8), TDS (50 percent), chloride (50 percent), and sulfate (50 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Niobrara confining unit in the CBS also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (44 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 4,360 to 57,500 mg/L, with a median of 29,000 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (50 percent; SMCL of 300 μg/L), sulfate (43 percent), and pH (22 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), sulfate (57 percent), iron (50 percent; WDEQ Class II standard of 5,000 μg/L), and pH (11 percent above upper WDEQ Class II limit of 9.0). Concentrations of two characteristics and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (78 percent), chloride (78 percent), and pH (22 percent above upper WDEQ Class III limit of 8.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 67 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Niobrara confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (6,120 and 10,300 mg/L) indicated that waters ranged from moderately to very saline (**Appendix F5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards: TDS and chloride in both samples. Sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards in one sample. The State of Wyoming Class IV standard for TDS was exceeded in one of the produced-water samples.

Great Plains

The chemical composition of groundwater in the Niobrara confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of 42 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram C**). TDS concentrations were variable and indicated that most waters were very saline (40 percent of samples) or briny (TDS concentrations greater than 34,999 mg/L) (40 percent of samples), and remaining waters were moderately saline (**Appendix F6**; **Appendix H4**, **diagram C;** supplementary data tables). TDS concentrations ranged from 3,550 to 112,000 mg/L, with a median of 27,200 mg/L.

Concentrations of some characteristics and constituents in water from the Niobrara confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (100 percent), pH (5 percent below lower SMCL limit of 6.5 and 2 percent above upper SMCL limit of 8.5), and sulfate (4 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (60 percent), and sulfate (7 percent). Characteristics and constituents in produced-water samples measured at concentrations at greater than State of Wyoming livestock-use standards were TDS (90 percent), chloride (90 percent), and pH (5 percent below lower WDEQ Class III limit of 6.5 and 2 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 81 percent of produced-water samples.

7.3.10 Frontier aquifer

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

Physical characteristics

The Frontier aquifer consists of the Late Cretaceous Frontier Formation (**Plates J, K, S, T, U**), which is present throughout most of the PtRB with the exception of the Granite Mountains area, with outcrops occurring near the uplifts (**Plates 1, 2**). The Frontier Formation is predominately a dark-gray shale with beds of sandstone near the top (Wall Creek Sandstone Member). In the Shirley Basin, Harshman (1968, 1972) described the lower part of the formation as dark-gray carbonaceous shale and the upper part as similar shale with interbedded gray to brownish-gray fine- to medium-grained sandstone. Harshman (1968, 1972) described the upper part of the Wall Creek Sandstone as a series of fine-to coarse-grained buff to greenish-gray sandstone beds that are interbedded with dark-gray shale. He also noted that the basal part can be a reddish to purplish-gray siltstone or sandy siltstone in some areas, whereas other areas have a basal part that is a gray, silty sandstone and shale. In the Hanna and Carbon Basins, the Frontier Formation is described as a dark-gray to black shale, and the Wall Creek Sandstone Member is described as sandstone interbedded with some shale (Dobbin, Bowen, and Hoots, 1929). In the western part of Carbon County, the Frontier Formation is described as gray to grayish-brown calcareous silty to sandy shale that has lenses of bentonite and beds of fine- to medium-grained sandstone (Berry, 1960; Merewether and Cobban, 1972). Merewether and Cobban (1972) referred to the lower part as the Belle Fourche Shale Member and the upper part as the Wall Creek Sandstone Member. They described an unnamed middle member as brownish-gray carbonaceous siltstone and shale or silty very fine- to fine-grained sandstone. In the adjacent Wind River Basin (WRB) and Wind River Mountains, this unnamed middle member has been named the Emigrant Gap Member (Johnson et al., 2007, and references therein).

The Frontier Formation is a marine deposit that accumulated on shallow shelves as channel deposits and near-shore and offshore bars (Merewether et al., 1979). The Frontier Formation ranges from 500- to 1,230-ft thick (Merewether and Cobban, 1972). The Wall Creek Sandstone Member ranges from 40 to 350 ft in thickness (Dobbin, Hoots, et al., 1929; Merewether and Cobban, 1972).

The Frontier Formation is defined as an aquifer by previous investigators. Development of the aquifer has been very limited because of the availability of shallower and better sources of groundwater and availability of surface water in areas where the formation crops out (Richter, 1981a). Sandstone beds within the aquifer, primarily in the Wall Creek Sandstone Member, are used primarily to supply water for stock purposes, but occasionally are used to supply water for domestic purposes (Berry, 1960; Whitcomb and Lowry, 1968; Collentine et al., 1981; Richter, 1981a, b). In the Rawlins Uplift area, Berry (1960, p. 20) noted that sandstone beds in the Frontier Formation "yield moderate amounts of water." He noted that water in the Frontier aquifer generally is under confined conditions (artesian pressure) and that wells completed in the aquifer will flow at some locations. Collentine et al. (1981) defined the formation as a "secondary aquifer" confined above by shale of the Cody or Niobrara confining units and below by the Mowry confining unit in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. He (Richter, 1981a, p. 70) reported that little hydraulic information was available describing the Frontier aquifer in the general vicinity of the Laramie, Shirley, and Hanna Basins, but development potential for groundwater supplies was "good" because of good primary permeability and saturation in upper sandstones, as well as "extensive" areas of potential recharge where the aquifer crops out along the Laramie, Shirley, and Freezeout Mountains. In the adjacent WRB, Richter (1981b, Table IV-1, p. 49) defined only the upper two-thirds of the Frontier Formation as a regional aquifer, and the lower one-third was defined as a confining unit. The Frontier aquifer is confined from above by the Cody or Niobrara confining units and confined from below by the Mowry-Thermopolis confining unit (**Plates J, K, S, T, U**). Hydrogeologic data describing the Frontier aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Water in the Frontier aquifer generally is under semiconfined or confined conditions, depending on confining layer continuity (Whitcomb and Lowry, 1968; Richter, 1981a, b). Richter (1981a, p. 70) noted that "semiconfined systems exist in the southern and central parts of the Laramie Basin where confining shales are elevated and dissected" and that "groundwater is confined in the northwestern part of the Laramie Basin because the unit is buried and confining units are continuous." In the WRB adjacent to the PtRB, alternating layers of sandstone and shale creates a series of confined sandstone subaquifers within the Frontier aquifer (Richter, 1981b, p. 76); it is likely this hydrogeologic interpretation of the Frontier aquifer is applicable to the unit throughout the PtRB.

Collentine et al. (1981) summarized hydraulic properties for the Frontier aquifer in the Great Divide and Washakie Basins. The area of the aquifer within Carbon County, on the eastern margin of the Great Divide and Washakie Basins, was considered the most "productive." Variability in transmissivity estimated from aquifer and drill-stem tests was attributed to varying percentages of bentonite and shale within tested open intervals. In addition, the investigators constructed a generalized potentiometric map for the Frontier aquifer within the basins, including Carbon County (Collentine et al., 1981, Figure V-4, p. 63). The map shows that groundwater flow in the area generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Chemical characteristics

The chemical characteristics of the Frontier aquifer are described in this section the report. In addition, the chemical characteristics of produced-water samples from one member of the Frontier Formation (Wall Creek Sandstone Member) identified by petroleum producers are described. Groundwater quality of the Frontier aquifer is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Frontier aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 1,280 to 3,330 mg/L, with a median of 1,740 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and fluoride (33 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), SAR (33 percent; WDEQ Class II standard of 8), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), and boron (33 percent; WDEQ Class II standard of 750 μg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Frontier aquifer in the SA also was characterized and the quality evaluated on the basis of four produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 2,150 to 10,100 mg/L, with a median of 8,290 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (75 percent; SMCL of 250 mg/L), pH (50 percent above upper limit), iron (50 percent; SMCL of 300 μg/L), and sulfate (25 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent; WDEQ Class II standard of 100 mg/L), iron (50 percent; WDEQ Class II standard of 5,000 μg/L), and sulfate (25 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (75 percent; WDEQ Class III standard of 5,000 mg/L), chloride (75 percent; WDEQ Class III standard of 2,000 mg/L), and pH (50 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 25 percent of produced-water samples.

Central Wyoming basins (south)

The chemical composition of groundwater in the Frontier aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (358 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for most uses. One characteristic (SAR) exceeded State of Wyoming agricultural-use standards.

The chemical composition of groundwater in the Frontier aquifer in the CBS also was characterized and the quality evaluated on the basis of 26 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram A**). TDS concentrations were variable and indicated that most waters were very saline (62 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations great than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram A**; supplementary data tables). TDS concentrations ranged from 3,210 to 47,600 mg/L, with a median of 12,200 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), iron (50 percent), pH (25 percent above upper SMCL limit of 8.5 and 4 percent below lower SMCL limit of 6.5), and sulfate (13 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), and sulfate (17 percent). Characteristics and constituents in produced-water samples measured at concentrations greater than State of Wyoming livestock-use standards were TDS (96 percent), chloride (96 percent), and pH (25 percent above upper WDEQ Class III limit of 8.5 and 4 percent below lower WDEQ Class III limit of 6.5). The State of Wyoming Class IV standard for TDS was exceeded in 69 percent of produced-water samples.

Sierra Madre

The chemical composition of groundwater in the Frontier aquifer in the Sierra Madre (SM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (714 mg/L) indicated that the water was fresh (**Appendix E3**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the SM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. Two characteristics (pH above upper limit and TDS) exceeded aesthetic standards for domestic use. Two characteristics (pH above upper WDEQ Class II limit of 9 and SAR) exceeded the State of Wyoming agricultural-use standards. One characteristic (pH above upper limit) exceeded State of Wyoming livestock-use standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Frontier aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (192 mg/L) indicated the water was fresh. On the basis of the few characteristics and constituents analyzed for, the quality of water from Frontier aquifer in the MBM was likely suitable for most uses. No characteristics or constituents in the Frontier aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental water sample.

Laramie Mountains

The chemical composition of groundwater in the Frontier aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E5**. TDS concentrations were highly variable and indicated that most waters were very saline (33 percent of samples), and remaining waters ranged from fresh to briny (**Appendix E5**; supplementary data tables). TDS concentrations ranged from 646 to 37,800 mg/L, with a median of 10,800 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: lead (100 percent; MCL (action level) of 15 μg/L; supplementary data tables), nitrate plus nitrite (in the one sample analyzed for this constituent; MCL of 10 mg/L), selenium (75 percent; MCL of 50 μg/L), strontium (50 percent; HAL of 4,000 μg/L), and fluoride (40 percent; MCL of 4 mg/L). Lead is not included in **Appendix E5** because values were too censored for the AMLE technique to calculate summary statistics. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), fluoride (40 percent), and chloride (17 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were selenium (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 20 μg/L), sulfate (100 percent), TDS (80 percent), boron (80 percent), SAR (50 percent), chloride (50 percent), and copper (50 percent; WDEQ Class II standard of 200 μg/L; supplementary data tables). Copper is not included in **Appendix E5** because values were too censored for the AMLE technique to calculate summary statistics. Characteristics and constituents in environmental water samples measured at greater than State of Wyoming livestock-use standards were selenium (75 percent; WDEQ Class III standard of 50 μg/L), TDS (60 percent), and sulfate (50 percent; WDEQ Class III standard of 3,000 mg/L). The State of Wyoming Class IV standard for TDS was exceeded in 60 percent of environmental water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Frontier aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as nine wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (56 percent of samples), and remaining waters ranged from fresh to moderately saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 708 to 3,570 mg/L, with a median of 1,470 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: fluoride (67 percent of samples analyzed for the constituent) and nitrate plus nitrite (33 percent). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (78 percent), fluoride (67 percent), and pH (22 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent of samples analyzed for the constituent), boron (100 percent), sulfate (89 percent), pH (22 percent above upper limit), TDS (22 percent), and chloride (22 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (22 percent above upper limit).

The chemical composition of groundwater in the Frontier aquifer in the CBN also was characterized and the quality evaluated on the basis of 22 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram B**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples), and remaining waters ranged from slightly to very saline (**Appendix F5**; **Appendix H3**, **diagram B;** supplementary data tables). TDS concentrations ranged from 2,260 to 34,100 mg/L, with a median of 6,850 mg/L.

Concentrations of some characteristics and constituents in water from the Frontier aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (91 percent), sulfate (45 percent), and pH (14 percent above upper limit and 5 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (95 percent), sulfate (55 percent), and pH (5 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (68 percent), chloride (55 percent), pH (14 percent above upper limit and 5 percent below lower limit), and sulfate (5 percent). State of Wyoming Class IV standard for TDS was exceeded in 36 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Frontier aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram D**). TDS concentrations were variable and indicated that most waters were briny (TDS concentrations greater than 34,999 mg/L) (64 percent of samples), and remaining waters ranged from fresh to very saline (**Appendix F6**; **Appendix H4**, **diagram D;** supplementary data tables). TDS concentrations ranged from 691 to 91,600 mg/L, with a median of 41,200 mg/L.

Concentrations of some characteristics and constituents in produced-water from the Frontier aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (100 percent), chloride (91 percent), and pH (45 percent below lower limit and 9 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent of samples analyzed for the constituent), iron (100 percent), TDS (91 percent), and pH (9 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (82 percent), chloride (82 percent), and pH (45 percent below lower limit and 9 percent above upper limit).The State of Wyoming Class IV standard for TDS was exceeded in 82 percent of produced-water samples.

7.3.10.1 Wall Creek Sandstone Member of Frontier Formation

Central Wyoming basins (north)

The chemical composition of groundwater in the Wall Creek Sandstone Member of Frontier Formation in the CBN also was characterized and the quality evaluated on the basis of 40 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram C**). TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from slightly to very saline (**Appendix F5**; **Appendix H3**, **diagram C;** supplementary data tables). TDS concentrations ranged from 2,300 to 18,300 mg/L, with a median of 3,010 mg/L.

Concentrations of some characteristics and constituents in water from the Wall Creek Sandstone Member of Frontier Formation in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (42 percent), chloride (92 percent), and pH (14 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (98 percent), and sulfate (46 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were: TDS (20 percent), chloride (18 percent), and pH (14 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 2 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Wall Creek Sandstone Member of the Frontier Formation in the GP also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for these samples are listed in **Appendix F6**. The TDS concentrations (3,340 and 3,410 mg/L) indicated that the water was moderately saline.

Concentrations of some characteristics and constituents in produced-water from the Wall Creek Sandstone Member of Frontier Formation in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS (both samples), chloride (both samples), and pH (one sample) exceeded aesthetic standards for domestic use. TDS and chloride exceeded agricultural-use standards in both samples. In one sample, pH (above upper limit) exceeded State of Wyoming livestock standards.

7.3.11 Carlile, Greenhorn, and Belle Fourche confining units

The physical and chemical characteristics of the Carlile, Greenhorn, and Belle Fourche confining units in the PtRB are described in this section of the report.

Physical characteristics

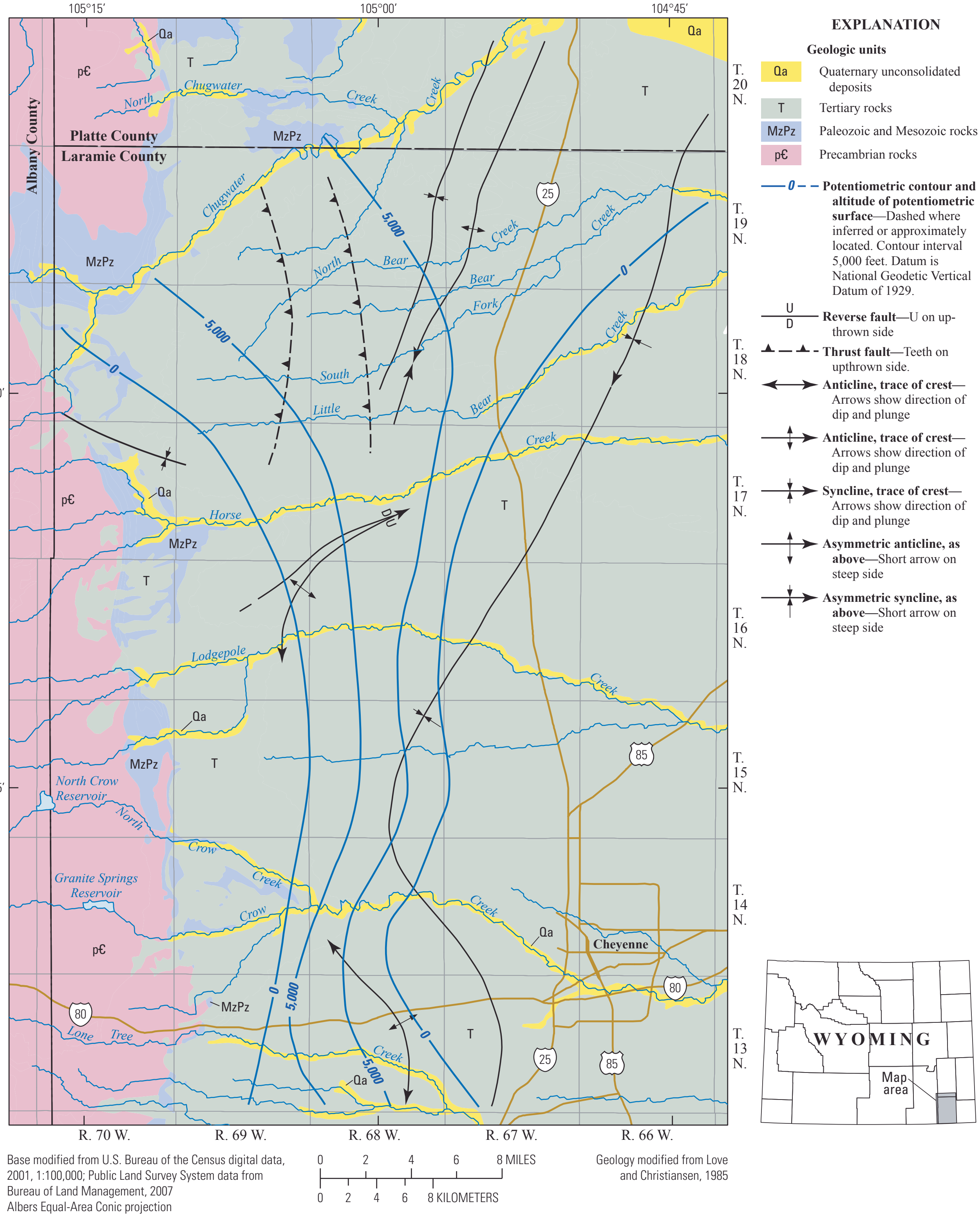
The Carlile, Greenhorn, and Belle Fourche confining units consist of the Late Cretaceous Carlile Shale, Greenhorn Formation, and Belle Fourche Shale, respectively (**Plate M**). All three confining units are composed primarily of shale with some limestone and sandstone (Love et al., 1993), and are deeply buried in the Denver-Julesburg Basin. The formations were deposited in a marine environment. Combined thickness of the three confining units in the Denver-Julesburg Basin is as much as 1,400 ft or more [these rocks were identified as the Frontier Formation consisting of "formations from top of Lower Cretaceous to base of Niobrara Formation" in Libra et al. (1981, Table IV-1, p. 40)].

Like the other Upper Cretaceous confining units composed primarily of shale deposited in a marine environment (Lewis, Cody, and Steele Shales, and the Niobrara Formation), shale is the predominant lithology in the Carlile Shale, Greenhorn Formation, and Belle Fourche Shale; consequently, all three lithostratigraphic units are defined as confining units (Libra et al., 1981) (**Plate M**). Libra et al. (1981, Table IV-1, p. 40) also noted that "dispersed sandstones might yield water."

Chemical characteristics

The chemical composition of groundwater in the Greenhorn confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (2,010 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L).

Concentrations of some characteristics and constituents in water from the Greenhorn confining unit in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 8.5, and 250 mg/L, respectively). TDS, chloride, and sulfate exceeded agricultural-use standards (WDEQ Class II standards of 2,000 mg/L,



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

Geology modified from Love and Christiansen, 1985

Figure 7-8. Generalized potentiometric-surface map for the Muddy Sandstone aquifer, Laramie County, Wyoming (modified from Wiersma, 1989).

100 mg/L, and 200 mg/L, respectively). One characteristic (pH above upper WDEQ Class III limit of 8.5) exceeded State of Wyoming livestock standards.

7.3.12 Mowry-Thermopolis confining unit and Muddy Sandstone aquifer

The physical and chemical characteristics of the Mowry-Thermopolis confining unit and Muddy Sandstone aquifer in the PtRB are described in this section of the report.

Physical characteristics

The Mowry-Thermopolis confining unit is composed primarily of the Mowry and Thermopolis Shales, but also contains the Muddy Sandstone aquifer (**Plates J, K, M, S, T, U**). The Mowry and Thermopolis Shales and the Muddy Sandstone are present throughout the PtRB, with outcrops occurring near the uplifts (**Plates 1, 2**).

The Late Cretaceous Mowry Shale is a gray to deep-brown to black siliceous marine shale with beds of bentonite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Welder and McGreevy, 1966; Harshman, 1972). Harshman (1972) noted that some of the bentonite beds are 2- to 3-ft thick and some are associated with shale beds that contain considerable calcium carbonate. The Mowry Shale is a marine shale that contains numerous fish scales. It ranges in thickness from 80 to 525 ft (Welder and McGreevy, 1966; Lowry and Crist, 1967; Harshman, 1972; Libra et al., 1981; Richter, 1981a, and references therein).

The Early Cretaceous Thermopolis Shale is a gray to black shale with thin beds of sandstone, siltstone, and bentonite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Welder and McGreevy, 1966; Harshman, 1972). The Early Cretaceous Muddy Sandstone, sometimes referred to as the Muddy Sandstone Member of the Thermopolis Shale in earlier publications, is a buff to gray, silty, fine- to medium-grained sandstone (Berry, 1960; Harshman, 1972). In earlier studies in the Denver-Julesburg Basin, the Thermopolis Shale commonly was identified as the "Skull Creek Shale" and the Muddy Sandstone as the "Newcastle Sandstone." Harshman (1972) described four parts of the Thermopolis Shale: (1) a basal gray to black carbonaceous shale; (2) the Muddy Sandstone; (3) a brown to gray fine-grained sandstone interbedded with siltstone and shale that has a lignite bed at the top with associated thin, limy sandstone beds; and (4) an interval of sandy siltstone and shale at the top interbedded with siliceous shale that is typical of the Mowry Shale. The Thermopolis Shale primarily is of marine origin; an exception is the third unit of Harshman (1972), which is of paludal (marsh-like) origin. Curry (1962) indicated that the Muddy Sandstone is of shallow marine origin in some parts and terrestrial and fresh-water origin in other parts. The Thermopolis Shale ranges in thickness from 70 to 200 ft or more (Welder and McGreevy, 1966; Lowry and Crist, 1967; Harshman, 1972; Lowry et al., 1973; Libra et al., 1981; Richter, 1981a, and references therein). The Muddy Sandstone ranges in thickness from 70 to 110 ft or more (Lowry and Crist, 1967; Libra et al., 1981, and references therein; Richter, 1981a, and references therein).

Like the previously described Lewis, Cody, and Steele Shales, and Niobrara Formation, shale is the predominant lithology in the Mowry and Thermopolis Shales; consequently, both units are considered to be regional confining units or leaky confining units throughout the PtRB (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Collentine et al., 1981; Libra et al., 1981; Richter, 1981a, b) (**Plates J, K, M, S, T, U**). The USGS defined the formations as "confining units" (Whitehead, 1996). In all parts of the PtRB except the Denver-Julesburg Basin, the Mowry-Thermopolis confining unit separates the underlying Cloverly aquifer from the overlying Frontier aquifer (**Plates J, K, S, T, U**). In the Denver-Julesburg Basin, the Mowry-Thermopolis confining unit underlies the Belle Fourche confining unit and overlies the Inyan Kara aquifer (**Plate M**).

The Muddy Sandstone between the Mowry and Thermopolis Shales is defined as an aquifer by all investigators, although many note that groundwater quality may preclude some uses (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973; Collentine et al., 1981; Libra et al., 1981; Richter, 1981a, b) (**Plates J, K, M, S, T, U**). The Muddy Sandstone aquifer is a major oil and gas reservoir in the PtRB. Permeability in the

Muddy Sandstone aquifer is generally low because of tight cementation and silty matrix; however, permeability can be fracture enhanced in some areas of deformation (Richter, 1981b, p. 75).

As a part of a study evaluating structural obstruction of recharge to Paleozoic hydrogeologic units in the western Denver-Julesburg Basin along the eastern flank of the Laramie Mountains, Wiersma (1989, Plate 1) and Wiersma et al. (1989, Plate 1) constructed a potentiometric-surface map of the Muddy Sandstone aquifer. The map, reproduced herein as **Figure 7-8**, indicates that the general direction of groundwater flow is to the east from the Laramie Mountains.

With the exception of oil and gas wells, very few wells are installed in the Mowry and Thermopolis confining units and the Muddy Sandstone aquifer; development is limited to low-yield wells located along the structural basin margins where the formations crop out and drilling depths are relatively shallow. Most hydrogeologic information describing the Mowry and Thermopolis confining units and the Muddy Sandstone aquifer is from oil and gas well data. Hydrogeologic information including well-yield and spring-discharge measurements and other hydraulic properties for the Mowry-Thermopolis confining unit and associated Muddy Sandstone aquifer is summarized on **Plate 3.**

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Muddy Sandstone aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of six produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (50 percent of samples) or moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (50 percent) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,520 to 7,090 mg/L, with a median of 3,260 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), iron (100 percent; SMCL of 300 μg/L), chloride (83 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (100 percent of samples analyzed for the constituent; WDEQ Class II standard 5,000 μg/L), chloride (83 percent; WDEQ Class II standard of 100 mg/L), TDS (67 percent; WDEQ Class II standard of 2,000 mg/L), sulfate (33 percent; WDEQ Class II standard of 200 mg/L), and pH (17 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (50 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Muddy Sandstone aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of 40 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram B**). TDS concentrations were variable and indicated that most waters were moderately saline (62 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram B**; supplementary data tables). TDS concentrations ranged from 1,380 to 18,300 mg/L, with a median of 6,250 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (85 percent), sulfate (39 percent), and pH (19 percent above upper SMCL limit of 8.5 and 6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (98 percent of samples analyzed for the constituent), TDS (90 percent), and sulfate (39 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (55 percent), chloride (52 percent), pH (19 percent above upper WDEQ Class III limit of 8.5 and 6 percent below lower WDEQ Class III limit of 6.5), and sulfate (3 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 15 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Mowry confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (1,320 mg/L) indicated that the water was slightly saline (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Mowry confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. Two constituents exceeded the State of Wyoming agricultural-use standards: boron (in the one sample analyzed for this constituent, the concentration was greater than the WDEQ Class II standard of 750 μg/L) and sulfate. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the LM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (76 mg/L) indicated that the water was fresh (TDS concentration less than or equal to 999 mg/L) (**Appendix E5**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Muddy Sandstone aquifer in the LM was suitable for most uses. No characteristics or constituents in the Muddy Sandstone aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards in the one environmental sample.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the LM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F4**. The TDS concentration (2,680 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and sulfate exceeded aesthetic standards for domestic use. TDS and sulfate exceeded State of Wyoming agricultural-use standards. One characteristic (pH above upper limit) exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Muddy Sandstone aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 51 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram D**). TDS concentrations were variable and indicated that most waters were moderately saline (41 percent of samples) or very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (41 percent of samples), and remaining waters were slightly saline (**Appendix F5**; **Appendix H3**, **diagram D;** supplementary data tables). TDS concentrations ranged from 1,360 to 16,700 mg/L, with a median of 8,490 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (in the one sample analyzed for this constituent), chloride (90 percent), sulfate (24 percent), and pH (8 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the one sample analyzed for this constituent), chloride (96 percent), TDS (92 percent), and sulfate (26 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (69 percent), chloride (67 percent), and pH (8 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 41 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Muddy Sandstone aquifer in the Great

Plains (GP) also was characterized and the quality evaluated on the basis of 31 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F6**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H4**, **diagram E**). TDS concentrations were variable and indicated that most waters were very saline (58 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F6**; **Appendix H4**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,240 to 50,300 mg/L, with a median of 11,000 mg/L.

Concentrations of some characteristics and constituents in water from the Muddy Sandstone aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (90 percent), iron (in one of two samples analyzed for this constituent), sulfate (43 percent), and pH (10 percent above upper limit and 3 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (97 percent of samples analyzed for the constituent), chloride (94 percent), sulfate (48 percent), and pH (3 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (84 percent), chloride (84 percent), pH (10 percent above upper limit and 3 percent below lower limit), and sulfate (5 percent). The State of Wyoming Class IV standard for TDS was exceeded in 61 percent of produced-water samples.

7.3.13 Cloverly aquifer

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

Physical characteristics

The Cloverly aquifer consists of the Early Cretaceous Cloverly Formation (**Plates J, K, S, T, U**), which is present throughout the basins of the PtRB, with outcrops occurring near the uplifts (**Plates 1, 2**). The Cloverly Formation has been divided into three parts: (1) an upper fine- to coarse-grained white to buff to gray quartzose sandstone, (2) a middle sequence of green shale to gray carbonaceous shale with interbedded buff, fine-grained, well-cemented, silty sandstone and some thin bentonite layers, and (3) a lower light-gray to white, fine-to medium-grained to conglomeratic sandstone with chert pebbles (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960; Harshman, 1972). The upper part of the formation is equivalent to the Dakota Sandstone, the middle part to the Fuson Shale, and the lower part to the Lakota Sandstone of adjacent areas (Agatston, 1951). Based on fossil assemblages, Curry (1962, p. 118) reported that terrestrial and fresh-water depositional environments probably persisted during the Early Cretaceous Epoch in central Wyoming. He also stated that considerable evidence exists that the uppermost fluvial deposits of the Cloverly Formation were partially reworked by the advancing Cretaceous seas (Curry, 1962, p. 118). The Cloverly Formation ranges from 50- to 200-ft in thickness in the Laramie, Shirley, and Hanna Basins (Harshman, 1972; Richter, 1981a, and references therein). In the area between Miller Hill and Rawlins, the average thickness of the Cloverly Formation has been estimated to be about 90 ft (Anderson and Kelly, Inc., 1984, p. 24).

The Cloverly Formation is defined as an aquifer by previous investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973;

Collentine et al., 1981; Richter, 1981a). Collentine et al. (1981) defined the formation as a “major aquifer” in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a “major aquifer” in the general vicinity of the Laramie, Shirley, and Hanna Basins. The USGS also defined the formation as a “principal aquifer” (Whitehead, 1996) and referred to the aquifer as part of the “Lower Cretaceous aquifers” category on the national principal aquifers map (U.S. Geological Survey, 2013). The Cloverly aquifer is confined from above by the Mowry-Thermopolis confining unit (**Plates J, K, S, T, U**) and confined from below by the Morrison confining unit (**Plates J, S**) or Morrison aquifer and confining unit (**Plates K, T, U**). The Cloverly aquifer is used as a source of water for stock, domestic, and public-supply purposes. Stock and domestic wells generally are completed in the Cloverly aquifer only in areas where the Cloverly Formation crops out. Hydrogeologic data describing the Cloverly aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

In the Rawlins Uplift area, Berry (1960, p. 19) described the Cloverly Formation as an artesian aquifer with “sufficient pressure to flow at the land surface.” He also reported that water from the Cloverly aquifer was the best quality for domestic and municipal use of all hydrogeologic units he examined in the Rawlins Uplift area.

In a study evaluating further development of the municipal water supply for the city of Rawlins, James M. Montgomery, Consulting Engineers, Inc. (1983b) conducted a new aquifer test of a well (“Rawlins-Cloverly well”) previously examined by Berry (1960). They reported that the similarity in transmissivity estimates from different aquifer tests suggested “regional homogeneity” for the Cloverly aquifer in the area.

Collentine et al. (1981) described the hydrogeology of the Cloverly aquifer in the Great Divide and Washakie Basins. The area of the aquifer on the eastern margin of the Great Divide in the vicinity of the Rawlins Uplift was defined as a “major Mesozoic aquifer.” The investigators noted that the Cloverly aquifer was deeply buried throughout most of the Great Divide and Washakie Basin areas. In addition, the investigators constructed a generalized potentiometric map for the Cloverly aquifer within the basins, including the western part of Carbon County (Collentine et al., 1981, Figure V-5, p. 65). The map shows that groundwater flow in the aquifer in Carbon County generally is towards the west, away from the outcrop areas (and source of recharge), and towards the Great Divide and Washakie Basin centers.

Richter (1981a) described the Cloverly aquifer in the Laramie, Shirley, and Hanna Basin areas. The investigator reported that the aquifer was confined throughout the area and had “good” intergranular porosity and permeability. Richter (1981a) also stated that there were two permeable zones within the Cloverly Formation—the Lakota and Dakota Sandstones separated by the Fuson Shale. He considered the Lakota and Dakota Sandstones as “subaquifers” within the Cloverly Formation, separated by the Fuson Shale, which he defined as a leaky confining unit allowing hydraulic connection through faults and fractures. He also noted that transmissivity was larger in “tectonically deformed areas.” Richter (1981a) also stated that the Lakota Sandstone was the most productive zone within the Cloverly Formation.

Wells completed in the Lakota and Dakota subaquifers of the Cloverly aquifer provide the public-water supply for the town of Elk Mountain (Weston Engineering, Inc., 1995a, b). The Cloverly aquifer is the only source of drinking water for the town. Consequently, the Cloverly aquifer in the vicinity of the town received a “sole-source aquifer” designation by the USEPA in 1998 (U.S. Environmental Protection Agency, 2005). The EPA defines a sole aquifer as “an aquifer that supplies at least 50 percent of the drinking water consumed in the area overlying the aquifer. These areas may have no alternative drinking water source(s) that could physically, legally and economically supply all those who depend on the aquifer for drinking water. For convenience, all designated sole or principal source aquifers are referred to as “sole source aquifers” (SSAs).” The designation prohibits the use of federal funds for any project which could pollute the sole source aquifer. This is the only “sole-source aquifer” designation in the entire State of Wyoming.

In their study of the Cloverly aquifer in the vicinity of Miller Hill, Anderson and Kelly, Inc. (1984, p. 25) speculated that recharge to the Cloverly aquifer occurs in three ways:

direct infiltration of precipitation on outcrops; infiltration from perennial streamflow losses; and interformational movement. They noted that recharge from direct infiltration of precipitation on outcrops is likely "significant" because of Cloverly aquifer outcrop in the study area. The investigators (Anderson and Kelly, Inc., 1984, p. 25) hypothesized that the Cloverly aquifer may receive recharge from "extensive areas of subcrop beneath the Tertiary deposits in Miller Hill."

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Cloverly aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well and two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (67 percent of samples) and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 241 to 2,680 mg/L, with a median of 484 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L and the alternative MCL of 4,000 pCi/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (33 percent; USEPA SMCL of 500 mg/L), and sulfate (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (33 percent of samples analyzed for the constituent; WDEQ Class II standard 8), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), and sulfate (33 percent; WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Cloverly aquifer in the SA also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were slightly saline (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,530 to 5,190 mg/L, with a median of 3,780 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), iron (in the one sample analyzed for this constituent; SMCL of 300 μg/L), chloride (67 percent; SMCL of 250 mg/L), pH (33 percent above upper SMCL limit of 8.5), and sulfate (33 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the one sample analyzed for this constituent; WDEQ Class II standard of 5,000 μg/L), TDS (67 percent), chloride (67 percent; WDEQ Class II standard of 100 mg/L), and sulfate (33 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (33 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Cloverly aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as nine wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (78 percent of samples) and remaining waters ranged from slightly to moderately saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 188 to 4,480 mg/L, with a median of 282 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: fluoride (12 percent; USEPA MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (50 percent), TDS (33 percent), fluoride (25 percent; SMCL of 2 mg/L), pH (43 percent above upper limit), chloride (22 percent), and sulfate (22 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (80 percent), pH (43 percent above upper WDEQ Class II limit of 9), TDS (22 percent), chloride (22 percent), sulfate (22 percent), and boron (12 percent; WDEQ Class II standard of 750 μg/L). Concentrations of one constituent and one characteristic were measured at greater than State of Wyoming livestock-use standards: mercury (in one of two samples analyzed for the constituent; WDEQ Class III standard of 0.05 μg/L) and pH (43 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the CBS also was characterized and the quality evaluated on the basis of 72 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram C**). TDS concentrations were variable and indicated that most waters were moderately saline (46 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram C;** supplementary data tables). TDS concentrations ranged from 1,020 to 24,100 mg/L, with a median of 4,730 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (in the two samples analyzed for this constituent), chloride (81 percent), sulfate (36 percent), and pH (22 percent above upper SMCL limit of 8.5 and 2 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were iron (in the two samples analyzed for this constituent), chloride (94 percent), TDS (82 percent), and sulfate (39 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were chloride (49 percent), TDS (47 percent), pH (22 percent above upper WDEQ Class II limit of 8.5 and 2 percent below lower WDEQ Class II limit of 6.5), and sulfate (3 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 18 percent of produced-water samples.

Medicine Bow Mountains

The chemical composition of groundwater in the Cloverly aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from two wells and one spring. Individual constituent concentrations are listed in **Appendix E4**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 112 to 168 mg/L, with a median of 168 mg/L. On the basis of the characteristics and constituents analyzed, the quality of water from the Cloverly aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Cloverly aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Cloverly aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 3 wells and 10 springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram A**). TDS concentrations were variable and indicated that most waters were fresh (85 percent of samples), and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram A**; supplementary data tables). TDS concentrations ranged from 228 to 2,090 mg/L, with a median of 419 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (46 percent of samples analyzed for the constituent), pH (33 percent above upper limit), fluoride (15 percent), and sulfate (15 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent of samples analyzed for the constituent), sulfate (31 percent), and TDS (8 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (33 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the LM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F4**. The TDS concentration (1,200 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and pH exceeded aesthetic standards for domestic use. One characteristic (pH above upper limit) exceeded State of Wyoming livestock standards. No characteristics or constituents exceeded State of Wyoming agriculture standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Cloverly aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as five wells. Individual constituent concentrations are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were slightly saline (60 percent of samples), and remaining waters were fresh (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 322 to 1,770 mg/L, with a median of 1,290 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: ammonia (33 percent; WDEQ Class I standard of 0.5 mg/L) and fluoride (20 percent). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (60 percent), fluoride (60 percent), sulfate (60 percent), manganese (33 percent; SMCL of 50 μg/L), and pH (40 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (100 percent), boron (60 percent), and sulfate (60 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (40 percent above upper limit).

The chemical composition of groundwater in the Cloverly aquifer in the CBN also was characterized and the quality evaluated on the basis of 104 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram E**). TDS concentrations were variable and indicated that most waters were slightly saline (39 percent of samples) and remaining waters ranged from moderately to very saline (**Appendix F5**; **Appendix H3**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,040 to 19,600 mg/L, with a median of 3,730 mg/L.

Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (80 percent), sulfate (50 percent), iron (in one of three samples analyzed for this constituent), and pH (10 percent above upper limit and 3 percent below lower limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (88 percent of samples analyzed for the constituent), TDS (77 percent), and sulfate (54 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (41 percent), chloride (38 percent), pH (10 percent above upper limit and 3 percent below lower limit), and sulfate (10 percent). The State of Wyoming Class IV standard for TDS was exceeded in 25 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Cloverly aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (385 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Cloverly aquifer in the GP was suitable for most uses. No characteristics or constituents in the Cloverly aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Cloverly aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentrations (9,030 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Cloverly aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards. TDS and chloride exceeded aesthetic standards for domestic use and State of Wyoming agricultural and livestock standards.

7.3.14 Inyan Kara aquifer

The Inyan Kara aquifer consists of the Early Cretaceous Inyan Kara Group and is present only in the Denver-Julesburg Basin (**Plates 1, 2**) (**Plate M**). The Inyan Kara Group has been divided into the upper Fall River Formation and the lower Lakota Formation. The lithostratigraphic unit has been previously referred to and is considered equivalent to the Cloverly Formation (Love and Christiansen, 1985, Sheet 2; Love et al., 1993). The formation is composed of "rusty to light-gray sandstone containing lenticular, chert-pebble conglomerate interbedded with variegated bentonitic claystone" (Love and Christiansen, 1985, Sheet 2). The Inyan Kara Group (identified as the Cloverly Formation) ranges from 0- to 300-ft in thickness in the Denver-Julesburg Basin (Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981). The Inyan Kara Group (identified as the Cloverly Formation) was considered a potential aquifer or minor aquifer by previous investigators (Morris and Babcock, 1960; Lowry and Crist, 1967; Libra et al., 1981) and consequently, the unit was defined as an aquifer herein (**Plate M**).

7.3.15 Morrison confining unit or Morrison aquifer and confining unit

The physical and chemical characteristics of the Morrison confining unit or Morrison aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Morrison confining unit or Morrison aquifer and confining unit consists of the Late Jurassic Morrison Formation (**Plates J, K, M, S, T, U**), which is present throughout the basins of the PtRB with outcrops present near the uplifts (**Plates 1, 2**). The Morrison Formation consists of interbedded buff, gray, green, maroon, and red shale; clayey siltstone; buff to yellow siltstone; buff to brown, partly calcareous, fine- to medium-grained sandstone; and some thin limestone lenses (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960; Harshman, 1972). The Morrison Formation has a maximum thickness of 325 ft in the Rawlins

Uplift area (Berry, 1960). Reported thickness in the Laramie, Shirley, and Hanna Basins area ranges from 125 to 320 ft (Richter, 1981a, Table IV-1, and references therein). Reported thickness in the Denver-Julesburg Basin ranges from 125 to 320 ft (Rapp et al., 1957, unnumbered table, p. 22; Morris and Babcock, 1960, Table 1, p. 22; Lowry and Crist, 1967, Table 1, p. 10; Libra et al., 1981, Table IV-1, and references therein).

Because of predominantly fine-grained composition and inferred low permeability, the Morrison Formation generally is defined as a regional confining unit (defined herein as the Morrison confining unit) or a regional confining with locally occurring discontinuous sandstone aquifers (defined herein as the Morrison aquifer and confining unit) (**Plates J, K, M, S, T, U**). With the exception of the Denver-Julesburg Basin, the Morrison confining unit or Morrison aquifer and confining unit is overlain by the Cloverly aquifer and underlain by the Sundance aquifer (**Plates J, K, S, T, U**). In the Denver-Julesburg Basin, the Morrison aquifer and confining unit is overlain by the Inyan Kara aquifer and underlain by the Sundance aquifer (**Plate M**).

Previous investigators have noted that discontinuous sandstone beds interbedded with finer-grained rocks in the Morrison confining unit or Morrison aquifer and confining unit will yield small quantities of water to wells adequate only for stock or domestic use where water quality is adequate; water from the hydrogeologic unit likely is too mineralized for many uses in many areas (Robinson, 1956; Burritt, 1962; Crist and Lowry, 1972; Libra et al., 1981; Richter, 1981a; Younus, 1992). Richter (1981a, Table IV-2, p. 51) reported that some "saturated discontinuous basal sandstone lenses had been encountered in petroleum test wells near Medicine Bow." Artesian conditions likely predominate, except in outcrop areas where unconfined (water table) conditions are possible (for example, Robinson, 1956; Burritt, 1962). Very few wells are installed in the Morrison confining unit or Morrison aquifer and confining unit, but available hydrogeologic data, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Morrison confining unit and Morrison aquifer and confining unit likely is from infiltration of precipitation and streamflow at outcrop areas. Robinson (1956) and Burritt (1962) reported that alluvium overlying the Morrison confining unit recharges the unit in parts of the Laramie Basin.

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 315 to 450 mg/L, with a median of 445 mg/L. On the basis of the characteristics and constituents analyzed, the quality of water from the Morrison confining unit or Morrison aquifer and confining unit in the SA was suitable for most uses. No characteristics or constituents in the Morrison confining unit or Morrison aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards on the basis of the environmental water samples.

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the SA also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (4,330 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in produced-water from the Morrison confining unit or Morrison aquifer and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, pH, and chloride exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, upper limit of 8.5, and 250 mg/L, respectively). TDS and chloride exceeded agricultural-use standards (WDEQ Class II standards of 2,000 mg/L and 100 mg/L, respectively). One characteristic (pH above upper WDEQ Class III limit of 8.5) exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of five produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were moderately saline (80 percent of samples), and remaining waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 3,010 to 10,900 mg/L, with a median of 5,170 mg/L.

Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (60 percent), sulfate (60 percent; SMCL of 250 mg/L), and pH (20 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), chloride (100 percent), and sulfate (60 percent; WDEQ Class II standard of 200 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (60 percent; WDEQ Class III standard of 5,000 mg/L), chloride (40 percent; WDEQ Class III standard of 2,000 mg/L), and pH (20 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 20 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (1,030 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the

LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Morrison confining unit or Morrison aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (18,600 mg/L) indicated that the water was very saline. Concentrations of some characteristics and constituents in water from the Morrison confining unit or Morrison aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards. TDS and chloride exceeded State of Wyoming livestock standards. The WDEQ Class IV standard for TDS was exceeded in the sample.

7.3.16 Sundance aquifer

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

Physical characteristics

The Middle and Late Jurassic Sundance Formation, which contains the Sundance aquifer, is present throughout the basins of the PtRB, with outcrops near the uplifts (**Plates 1, 2**) and deeply buried elsewhere. As many as seven members of the Sundance Formation have been described: Windy Hill, Redwater Shale, Pine Butte, Lak, Hulett, Stockade Beaver Shale, and Canyon Springs Members (Pipiringos, 1968; Harshman, 1972). The uppermost Windy Hill Member is a buff to gray, very fine-to medium-grained, thin-bedded, limy oolitic sandstone or a fine-to coarse-grained calcite-cemented sandstone with gray-green to dark-gray shale partings (Pipiringos, 1968; Harshman, 1972). Peterson (1994) reassigned the Windy Hill Member to the basal part of the Morrison Formation, even though this member is a marine unit, whereas most of the Morrison is non-marine. The Redwater Shale Member is greenish or yellowish-gray shale and clayey siltstone with some firmly lime-cemented coquinoid sandstone or sandy coquinoid limestone (Pipiringos, 1968; Harshman, 1972). The Pine Butte Member is greenish white, firmly lime-cemented sandstone with interbedded greenish to yellowish-gray glauconitic siltstone and clay shale (Pipiringos, 1968; Harshman, 1972). The Lak Member is pink to reddish-brown to yellowish-white fine- to medium-grained sandstone, sandy siltstone, and siltstone (Pipiringos, 1968; Harshman, 1972). The Hulett Sandstone Member is fine-to medium-grained, buff to white sandstone with some shale and glauconite (Pipiringos, 1968, Harshman, 1972). The Stockade Beaver Shale Member is greenish-gray to greenish-yellow shale and siltstone (Pipiringos, 1968; Harshman, 1972). The Canyon Springs Member is light gray fine-grained oolitic to yellowish-white fine-to medium-grained sandstone with chert pebbles at the base in some areas (Pipiringos, 1968; Harshman, 1972). The Sundance Formation was deposited in a marine environment and is 195- to 365-ft thick (Pipiringos, 1968).

In the Granite Mountains Uplift and Shirley Basin, the Sundance aquifer is confined from above by the Morrison confining unit and underlain by either the Gypsum Spring confining unit or the

Nugget aquifer (**Plate J**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Goose Egg or Chugwater confining units in the Hartville Uplift and Laramie Mountains (**Plate K**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Chugwater confining unit in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Sundance aquifer is overlain by the Morrison aquifer and confining unit and confined from below by the Chugwater aquifer and confining unit (**Plate S**). The Sundance aquifer is overlain by the Morrison aquifer and confining unit and underlain by the Jelm aquifer or Chugwater confining unit in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

Despite little information available to describe the hydrogeologic characteristics of the Sundance Formation, all investigators consider all or parts of the lithostratigraphic unit to be an aquifer or potential aquifer, particularly in areas with substantial amounts of sandstone (for example, Berry, 1960; Welder and McGreevy, 1966; Lowry and Crist, 1967; Lowry et al., 1973; Collentine et al., 1981; Richter, 1981a, b). Littleton (1950b) and Robinson (1956) noted that sandstone beds in the unit were aquifers or potential aquifers in the Laramie Basin. In fact, Robinson (1956, p. 41) noted that the unit "lithologically is an excellent aquifer." Richter (1981a, p. 70-71) reported that the Sundance aquifer in the Laramie, Shirley, and Hanna Basins was composed of three "massive permeable sandstone members" separated by impermeable shales and sandstones, resulting in three confined subaquifers hydraulically integrated into one aquifer by faults and fractures. Collentine et al. (1981) defined the Sundance Formation as a "minor aquifer" in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. Both Collentine et al. (1981) and Richter (1981b) stated that the Sundance aquifer is in hydraulic connection with the underlying Nugget aquifer where present. Consequently, these investigators combined the Sundance aquifer and Nugget aquifer into a single aquifer or aquifer system defined as the "Sundance-Nugget aquifer," and that definition is retained herein for the parts of the PtRB where both units occur (**Plates J, S**).

Because of deep burial throughout most of the PtRB, most wells completed in the Sundance aquifer are oil wells and most information describing the hydrogeologic characteristics of the Sundance aquifer are from these types of deep wells. Collentine et al. (1981) noted artesian conditions in wells installed in the Sundance aquifer in the Rawlins Uplift area. In the Laramie, Shirley, and Hanna Basins, Richter (1981a, Table IV-2, p. 50) reported that basal sandstones of the Sundance aquifer have "large intergranular porosity and permeability" and "upper sands are well cemented and have low permeabilities." He reported artesian conditions in the basal sandstones with flows ranging from 1 to 50 gal/min. In parts of the Sundance aquifer (presumably the "upper sands"), primary (intergranular) permeability may be relatively small, but substantially larger in structurally deformed areas with fractures (Richter, 1981a). Hydrogeologic data describing the Sundance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Because of limited outcrop extent and small permeabilities, Richter (1981a, p. 71) speculated that much of the recharge to the Sundance aquifer in the Laramie, Shirley, and Hanna Basins is from interformational flow. Numerous springs and seeps discharge from the Sundance aquifer along the southwestern flank of the Laramie Mountains and northern flank of the Shirley and Freezeout Mountains (Richter, 1981a); reported discharge from these springs generally was less than 1 gal/min. The investigator (Richter, 1981a, p. 71) speculated that these "relatively small [spring] discharges indicate that the rocks have negligible permeabilities because available recharge to the rocks and those elevated areas is relatively large."

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Sundance aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from a spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (680 mg/L) indicated that the water was fresh (TDs concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; USEPA SMCL of 500 mg/L) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Sundance aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations indicated that waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 1,100 to 2,010 mg/L, with a median of 1,910 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: fluoride (50 percent); USEPA MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), fluoride (50 percent; SMCL of 2 mg/L), sulfate (67 percent), and pH (50 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (67 percent of samples analyzed for the constituent; WDEQ Class II standard 8), sulfate (67 percent), TDS (33 percent; WDEQ Class II standard of 2,000 mg/L), boron (33 percent; WDEQ Class II standard of 750 μg/L), and chloride (33 percent; WDEQ Class II standard of 100 mg/L). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5).

The chemical composition of groundwater in the Sundance aquifer in the CBS also was characterized and the quality evaluated on the basis of 18 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram D**). TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples) and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram D;** supplementary data tables). TDS concentrations ranged from 1,040 to 123,000 mg/L, with a median of 2,240 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (72 percent), chloride (39 percent; SMCL of 250 mg/L), and pH (35 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (78 percent of samples analyzed for the constituent), sulfate (72 percent), and TDS (61 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (35 percent above upper limit), TDS (17 percent; WDEQ Class III standard of 5,000 mg/L), chloride (17 percent; WDEQ Class III standard of 2,000 mg/L), and sulfate (6 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 11 percent of produced-water samples.

Laramie Mountains

The chemical composition of groundwater in the Sundance aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentrations (200 and 604 mg/L) indicated that the waters were fresh (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use in one sample. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards in one sample. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Sundance aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 17 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram F**). TDS concentrations were variable and indicated that most waters were slightly saline (65 percent of samples) and remaining waters ranged from moderately saline (3,000 to 9,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F5**; **Appendix H3**, **diagram F;** supplementary data tables). TDS concentrations ranged from 1,170 to 16,600 mg/L, with a median of 2,460 mg/L.

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (88 percent), chloride (47 percent), and pH (40 percent above upper SMCL limit of 8.5 and 7 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (88 percent of samples analyzed for the constituent), sulfate (88 percent), and TDS (76 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (40 percent above upper WDEQ Class III limit of 8.5 and 7 percent below lower WDEQ Class III limit of 6.5), TDS (12 percent), chloride (12 percent), and sulfate (12 percent). The State of Wyoming Class IV standard for TDS was exceeded in 6 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Sundance aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (260 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Sundance aquifer in the GP was suitable for most uses. No characteristics or constituents in the Sundance aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Sundance aquifer in the GP also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F6**. TDS concentrations (2,680 and 3,830 mg/L) indicated that most waters were slightly to moderately saline (**Appendix F6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Sundance aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Two characteristics (pH above upper limit in one sample and TDS in both samples) and two constituents (chloride in one sample and sulfate in both samples) exceeded aesthetic standards for domestic use. One characteristic (TDS) and two constituents (chloride and sulfate) exceeded the State of Wyoming agricultural-use standards in both samples. One characteristic (pH above upper limit) exceeded the State of Wyoming livestock-use standards in one sample.

7.3.17 Gypsum Spring confining unit

Composed of an interbedded sequence of shale, siltstone, limestone, dolomite, and gypsum, the Gypsum Spring Formation comprises the Gypsum Spring confining unit (**Plate J**). The hydrogeologic unit was classified as a regional leaky confining unit by Richter (1981b) and the confining unit designation is retained herein. No additional information was located describing the physical and chemical hydrogeologic characteristics of the Gypsum Spring confining unit in the PtRB, so additional description as part of this study was not possible.

7.3.18 Nugget aquifer

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

Physical characteristics

The Nugget Sandstone, which contains the Nugget aquifer, is present in the subsurface in parts of the PtRB, with some outcrops occurring near uplifts (**Plates 1, 2**). The Nugget Sandstone is a very fine-to coarse-grained buff to white to pink highly porous sandstone (Pipiringos, 1957, 1968;

Berry, 1960). Pipiringos (1968) also described a lower Bell Springs Member that is red and gray sandstone with red, green, and pale-purplish-red to pale-red siltstone and shale. Pipiringos (1957) noted that the formation may be of eolian and (or) subaqueous origin. Berry (1960) estimated a maximum thickness of 110 ft in the subsurface in the vicinity of the Rawlins Uplift. Richter (1981a, Table IV-2, p. 50, and references therein) reported that the Nugget Sandstone in the Laramie, Shirley, and Hanna Basins area ranged from 50 to 100 ft in thickness. Collentine et al. (1981, Table IV-2, p. 50) reported that the Nugget Sandstone in the Great Divide and Washakie Basins area ranged from 0 to 650 ft or more in thickness.

Early investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of the Nugget aquifer. Collentine et al. (1981) defined the Nugget Sandstone as a "minor aquifer" in the Great Divide and Washakie Basins. Similarly, Richter (1981a) defined the formation as a "secondary aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins. Both Collentine et al. (1981) and Richter (1981a) stated that the Nugget aquifer is in hydraulic connection with the overlying Sundance aquifer in the Great Divide and Washakie Basins and Laramie, Shirley, and Hanna Basins, respectively. Consequently, these investigators combined the Nugget and Sundance aquifers in these areas into a single aquifer or aquifer system defined as the "Sundance-Nugget aquifer" and that definition is retained herein for the parts of the PtRB where both units occur (**Plates J, S**). The Nugget aquifer is confined from above by the Gypsum Spring confining unit where present or overlain from above by the Sundance aquifer; the unit is confined from below by the Popo Agie confining unit of the Chugwater aquifer and confining unit in the Granite Mountains Uplift, Shirley Basin, and Rawlins Uplift (**Plates J, S**). Hydrogeologic data describing the Nugget aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Because of deep burial throughout most of the PtRB, data describing the hydrogeologic characteristics of the Nugget aquifer primarily are from deep oil wells. In the Laramie, Shirley, and Hanna Basins, Richter (1981a, Table IV-2, p. 50) reported that basal sandstones have "large intergranular porosity and permeability." He reported artesian conditions in "deep basin wells" with flows ranging from 50 to 100 gal/min.

Most studies of the Nugget aquifer within the PtRB are associated with development of the public groundwater supply for the city of Rawlins (Anderson and Kelly, Inc., 1984; James M. Montgomery, Consulting, Engineers, Inc., 1982a, b; 1983a, b; 1986a, b; Western Water Consultants, Inc., 1997, and references therein). Some insight into the hydrogeologic characteristics of the Nugget aquifer is provided by these studies through construction and testing of Rawlins public (municipal) supply wells completed in the aquifer in the Miller Hill area. Anderson and Kelly, Inc. (1984) and James M. Montgomery, Consulting Engineers, Inc. (1982a, b; 1986a, b) described the hydrogeologic characteristics in the area on the basis of three public-supply wells completed in the aquifer. Anderson and Kelly, Inc. (1984) completed a 1,730-ft deep well into the Nugget aquifer. They noted that water flowed from the well at 350 gal/min from a thin zone in the upper part of the Nugget Sandstone. Subsequently, James M. Montgomery Consulting Engineers (1986a, b) completed two additional wells to a similar depth in the same area. Like Anderson and Kelly, Inc. (1984), the investigators noted that groundwater flow to the wells was primarily from thin discrete zones within the Nugget Sandstone. Aquifer tests were conducted at all three wells using both constant-drawdown and recovery methods. They reported that the aquifer was "highly productive" in the area. Based on conditions encountered during drilling and subsequent aquifer tests, James M. Montgomery Consulting Engineers (1986a, b) concluded that localized fracture zones (and therefore, secondary permeability) are responsible for most of the water yielded to wells completed in the Nugget aquifer in the Miller Hill area. They stated that the localized fracture zones are not present throughout the formation.

In their study of the Nugget aquifer in the vicinity of Miller Hill, Anderson and Kelly, Inc. (1984, p. 19) speculated that recharge to the Nugget aquifer occurs in three ways: direct infiltration of precipitation on outcrops; infiltration from perennial streamflow losses from McKinney, Littlefield, and Sage Creeks on outcrops; and interformational movement. They noted that recharge from direct infiltration of precipitation on outcrops is likely small because of limited Nugget aquifer outcrop in the study area. The investigators (Anderson and Kelly, Inc., 1984, p. 19) did not quantify recharge but they stated that "the opportunities for recharge are extensive" and the "good water quality of the Nugget well suggest a relatively active groundwater circulation system."

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Nugget aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentration ranging from 1,000 to 2,999 mg/L) (67 percent of samples) and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F1**; supplementary data tables). TDS concentrations ranged from 1,080 to 4,710 mg/L, with a median of 1,150 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL of 500 mg/L), sulfate (67 percent; SMCL of 250 mg/L), pH (50 percent above upper SMCL limit of 8.5), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (67 percent of samples analyzed for the constituent; WDEQ Class II standard 100 mg/L), sulfate (67 percent; WDEQ Class II standard of 200 mg/L), and TDS (33 percent; WDEQ Class II standard of 2,000 mg/L). One characteristic and one constituent in produced-water samples were measured at greater than State of Wyoming livestock-use standards: pH (50 percent above upper WDEQ Class III limit of 8.5) and chloride (33 percent; WDEQ Class III limit of 2,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Nugget aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations indicated that waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 596 to 913 mg/L, with a median of 673 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of two characteristics exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent) and pH (100 percent above upper limit).

For agricultural and livestock use, concentrations of one characteristic exceeded State of Wyoming standards in the CBS. Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (100 percent above upper limit). No characteristics or constituents exceeded State of Wyoming agricultural standards.

The chemical composition of groundwater in the Nugget aquifer in the CBS also was characterized and the quality evaluated on the basis of 16 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram E**). TDS concentrations were variable and indicated that most waters were moderately saline (62 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram E;** supplementary data tables). TDS concentrations ranged from 1,900 to 16,000 mg/L, with a median of 4,900 mg/L.

Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), chloride (88 percent), iron (in one of two samples analyzed for this constituent; SMCL of 300 μg/L), sulfate (36 percent), and pH (21 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent), TDS (94 percent), iron (in one of two samples analyzed for this constituent; WDEQ Class II standard of 5,000 μg/L), sulfate (36 percent), and pH (7 percent above upper WDEQ Class II limit of 9.0). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were chloride (56 percent), TDS (44 percent; WDEQ Class III standard of 5,000 mg/L), and pH (21 percent above upper limit). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 19 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Nugget aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (1,770 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Nugget aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. Sulfate exceeded State of Wyoming agricultural standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.19 Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit

The physical and chemical characteristics of the Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

The Jelm aquifer is composed of the Late Triassic Jelm Formation (**Plates T, U**). The Chugwater confining unit and Chugwater aquifer and confining unit are composed of the Permian and Triassic Chugwater Group or Formation and its various formations or members (**Plates J, K, M, S, T, U**). These lithostratigraphic units are present at or near land surface around most uplifts and throughout the subsurface of the PtRB (**Plates 1, 2**). Historically, the "Jelm" has been considered part of the Chugwater Group or Formation in some areas of the PtRB; in other areas, it has been mapped and described separately. The "Chugwater" has been assigned both formation and group rank; the unit has been divided into as many as five formations or members (Jelm Formation; Popo Agie Formation or Member, Crow Mountain Sandstone or Sandstone Member, Alcova Limestone or Limestone Member, and Red Peak Formation or Member), depending on rank of the lithostratigraphic unit assigned by different investigators in a given area of the PtRB. Some formations or members of the "Chugwater," where the lithostratigraphic unit is divided, are missing locally due to erosion or nondeposition.

The Jelm Formation was included in the Chugwater Group by Pipiringos (1968). He also divided it into the Sips Creek and Red Draw Members. The Sips Creek Member is a greenish-white to reddish-brown and yellow sandstone that is in part conglomeratic with pebbles of siltstone, limestone, and shale, and fragments of fossil wood and bone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). The upper part of the Sips Creek Member is a reddish-brown siltstone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). In the Shirley Basin, the Sips Creek Member is a tan to buff well-cemented sandstone (Harshman, 1972). It is a fluvial and lacustrine deposit (Pipiringos and O'Sullivan, 1978) that is 0- to 315-ft thick (Pipiringos, 1968). The Red Draw Member is reddish-brown shale, siltstone, and sandstone that is interbedded with some greenish-gray siltstone (Pipiringos, 1968; Harshman, 1972; Pipiringos and O'Sullivan, 1978). It is a fluvial deposit (Pipiringos and O'Sullivan, 1978) that is 0- to 140-ft thick (Pipiringos, 1968). The undivided Jelm Formation is as much as 360-ft thick (Pipiringos, 1968).

Where undivided and assigned formation rank, the Chugwater Formation is described as red shale and sandstone, with some purple, pink, green, and buff beds, and a few limestone and gypsum beds (Dobbin, Bowen, and Hoots, 1929; Dobbin, Hoots, et al., 1929; Berry, 1960). It is of fluvial, lacustrine, eolian, and marine origin (Pipiringos and O'Sullivan, 1978). The maximum thickness noted by Dobbin, Hoots, et al. (1929) is 1,350 ft.

Where divided into formations or members, the uppermost formation or member of the Chugwater Group or Formation is the Popo Agie Formation or Member (**Plates J, S**). The Popo Agie Formation is a purple to pale-red to ochre siltstone, analcime-rich claystone, silty claystone, and grayish-yellow sandstone (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). North and west of the Ferris Mountains, the Popo Agie Formation is divided into the Lyons Valley and Brynt Draw Members (Pipiringos, 1968; Pipiringos and O'Sullivan, 1978). It is a fluvial and lacustrine deposit (Pipiringos and O'Sullivan, 1978). The formation ranges from 0- to about 100-ft thick (Pipiringos, 1968).

The next formation or member of the Chugwater Group or Formation is the Crow Mountain Sandstone or Sandstone Member (Pipiringos, 1968) (**Plates J, S**). In the area southeast of the Granite Mountains, the name Crow Mountain was replaced with Jelm by Pipiringos (1968). The upper part of the Crow Mountain Sandstone is white to reddish-brown sandstone and siltstone with minor amounts of pale-red and green shale (Pipiringos and O'Sullivan, 1978). The lower part of the unit is salmon-red to reddish-brown sandstone with minor amounts of sandstone, siltstone, and some sandy clay shale (Pipiringos and O'Sullivan, 1978). The upper part is of fluvial origin, whereas the lower part is of marine origin

(Pipiringos and O'Sullivan, 1978). Pipiringos (1968, p. D11) showed a section that is 192-ft thick.

The next unit, the Alcova Limestone or Limestone Member (**Plates J, K, S**), is identified as part of the Chugwater Group or Formation by some investigators (Pipiringos, 1968; Harshman, 1972; Pipiringos and O'Sullivan, 1978) and as a member of the Crow Mountain and Jelm Formations by others (High and Picard, 1969). It is a gray, purple, greenish-gray, brownish-gray, and greenish-brown limestone that is sandy in its upper and lower parts (Harshman, 1972; Pipiringos and O'Sullivan, 1978). The Alcova Limestone is resistant and commonly forms prominent hogbacks. It is of marine origin (Pipiringos and O'Sullivan, 1978). The formation is missing locally due to erosion or nondeposition. Where present, it has a maximum thickness of 20 ft (High and Picard, 1969).

The Red Peak Formation or Member is the lowest unit of the Chugwater Group or Formation (Pipiringos, 1968) (**Plates J, K, S**). It is a pale to moderate reddish-brown to red siltstone with some interbedded thin yellowish-gray to white to pink, very fine-to fine-grained calcareous sandstone (Harshman, 1972; Lowry et al., 1973; Pipiringos and O'Sullivan, 1978). It is of marine origin (Pipiringos and O'Sullivan, 1978). Lowry et al. (1973) reported a thickness of 600 to 700 ft.

The Jelm aquifer is overlain by the Sundance aquifer and underlain by the Chugwater confining unit (**Plates T, U**). Little hydrogeologic information describing the Jelm aquifer could be located, but available hydrogeologic data describing the Jelm aquifer, including well-yield and other hydraulic properties, are summarized in **Plate 3**. Littleton (1950b, Table 1, p. 14) reported that the unit "may contain artesian water" in the Laramie Basin. Saulnier (1968) reported locally permeable zones in the north flank of the Medicine Bow Mountains and Pass Creek Basin area. Richter (1981a, Table IV-2, p. 50) noted that artesian conditions in basal sandstone and conglomerate of the Jelm aquifer in the Laramie, Shirley, and Hanna Basins could produce flows of 10 to 25 gal/min.

Regionally, most investigators consider the Chugwater Group or Formation to be a confining unit; however, locally permeable sandstones interbedded with low-permeability fine-grained lithologic units (shale, siltstone, limestone) occur throughout the unit, and wells commonly are completed in these sandstones throughout the PtRB. Consequently, the "Chugwater" may be considered a sequence of rocks that regionally functions as both aquifer and confining unit (**Plates J, K, M, S, T, U**), depending upon location examined and the scale of the study. In the Granite Mountains Uplift and Shirley Basin, the Chugwater aquifer and confining unit is overlain by the Nugget aquifer and underlain by either the Phosphoria aquifer and confining unit or the Dinwoody confining unit (**Plate J**). The Chugwater confining unit is overlain by the Sundance aquifer and underlain by the Forelle Limestone in the Hartville Uplift and Laramie Mountains (**Plate K**). The Chugwater confining unit is overlain by the Sundance aquifer and underlain by the Forelle Limestone in the Denver-Julesburg Basin (**Plate M**). In the Rawlins Uplift, the Chugwater aquifer and confining unit is overlain by the Nugget aquifer and underlain by the Goose Egg confining unit (**Plate S**). The Chugwater confining unit is overlain by the Sundance and Jelm aquifers and underlain by the Goose Egg confining unit and Forelle Limestone in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and the Hanna and Laramie Basins (**Plates T, U**).

Classification and reported hydrogeologic characteristics of the "Chugwater" varies by geographic region. In the WRB and Granite Mountains area, Richter (1981b, Table IV-1) classified the Popo Agie Formation and Alcova Limestone as confining units and the Crow Mountain and Red Peak Formations as aquifers/subaquifers; that classification is retained herein (**Plate J**). The Chugwater Group or Formation also is divided into these four lithostratigraphic units in the Rawlins Uplift, so the hydrogeologic unit classification of these four units by Richter (1981b) is retained for this geographic area as well (**Plate S**). The Crow Mountain and Red Peak aquifers/subaquifers may yield small quantities of water to wells and springs at some locations in the WRB and Granite Mountains area (Richter, 1981b). In the Rawlins Uplift area, Berry (1960, p. 17) reported that no known wells were completed in the Chugwater Formation in the area although "sandstone beds probably will yield small domestic and stock supplies," but then noted that "the water would probably be highly mineralized." Crist and Lowry (1972, p. 53) classified the Chugwater Group as a "low-yield aquifer" in Natrona County. Welder and McGreevy (1966, Sheet 3) reported that "groundwater possibilities were not known, but probably poor" in the Great Divide and Washakie Basins. Collentine et al. (1981) defined the Chugwater Formation as an "aquitard" and "confining unit" in the Great Divide and Washakie Basins, separating the overlying "Sundance-Nugget aquifer" from the underlying "Paleozoic aquifer system." Similarly, Richter (1981a) defined the Chugwater Formation as a regional leaky confining unit with locally permeable sandstones and fractured limestone interbeds in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plate K**). He also noted that basal sandstones were "water-bearing" in the Laramie Basin, but well yields were small (less than 10 gal/min) and waters were mineralized. Johnson (1994) and Johnson and Huntoon (1994) classified the Alcova Limestone and the Chugwater Formation as confining units in the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains (**Plate J**). Younus (1992, Figure 11, p. 25) classified the Chugwater Formation as a confining unit in the southern Laramie Basin and western flank of the Laramie Mountains, but the investigator noted that sandstone beds may yield mineralized water and may be classified as local aquifers. Sandstones in the Chugwater confining unit locally provide water to numerous wells in the Laramie Basin, primarily for stock and limited domestic uses (for example, Morgan, 1947; Robinson, 1956; Burritt, 1962; Lundy, 1978; Younus, 1992; Mazor, 1990; Mazor et al., 1993). Hydrogeologic data describing the Chugwater confining unit or Chugwater aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized in **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Jelm aquifer, Chugwater confining unit, and Chugwater aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

7.3.19.1 Jelm aquifer

Sweetwater Arch

The chemical composition of groundwater in the Jelm aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (1,840 mg/L) indicated that the water was slightly saline (TDS concentrations less than or equal to 999 mg/L). Concentrations of some characteristics and constituents in water from the Jelm aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but two characteristics (pH upper limit and TDS; USEPA SMCLs of 8.5 and 500 mg/L, respectively) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent exceeded State of Wyoming agricultural-use standards: sulfate (WDEQ Class II standard of 200 mg/L). One characteristic exceeded State of Wyoming livestock standards: pH (upper WDEQ Class III limit of 8.5).

Medicine Bow Mountains

The chemical composition of groundwater in the Jelm aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (492 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Jelm aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Jelm aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.19.2 Chugwater confining unit and Chugwater aquifer and confining unit

Sweetwater Arch

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the SA was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and three springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that waters were fresh (50 percent of samples) to slightly saline (50 percent of samples) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 264 to 2,440 mg/L, with a median of 1,500 mg/L.

Concentrations of some characteristics and constituents in water from the Chugwater confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L) and strontium (in the one sample analyzed for this constituent, the concentration exceeded the USEPA HAL of 4,000 μg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (75 percent) and sulfate (75 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (75 percent of samples analyzed for the constituent) and TDS (50 percent; WDEQ Class II standard of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (442 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater aquifer and confining unit in the CBS was suitable for most uses. No characteristics or constituents in the Chugwater aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Chugwater confining unit in the MBM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (314 mg/L) indicated that the water was fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater Group or Formation in the MBM was suitable for most uses. No characteristics or constituents in the Chugwater Group or Formation approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Chugwater confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 13 wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram B**). TDS concentrations were variable and indicated that most waters were slightly saline (78 percent of samples) and remaining waters were fresh (**Appendix E5**; **Appendix G3**, **diagram B**; supplementary data tables). TDS concentrations ranged from 456 to 2,890 mg/L, with a median of 1,550 mg/L.

Concentrations of some characteristics and constituents in water from the Chugwater confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded proposed MCL, but did not exceeded the alternative MCL). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (94 percent of samples analyzed for the constituent), sulfate (94 percent), pH (9 percent below lower SMCL limit of 6.5), and fluoride (9 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent) and TDS (33 percent). Concentrations of one characteristic was measured at greater than State of Wyoming livestock-use standards: pH (9 percent below lower WDEQ Class III limit of 6.5).

Central Wyoming basins (north)

The chemical composition of groundwater in the Chugwater aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentrations (2,830 and 3,760 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Chugwater aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS (both samples), chloride (one sample; SMCL of 250 mg/L), and sulfate (both samples) exceeded aesthetic standards for domestic use. In both samples, TDS, chloride (WDEQ Class II standard of 100 mg/L), and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Great Plains

The chemical composition of groundwater in the Chugwater confining unit in the Great Plains (GP) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E7**. The TDS concentration (436 mg/L) indicated that the water was fresh (**Appendix E7**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Chugwater confining unit in the GP was suitable for most uses. No characteristics or constituents in the Chugwater confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.19.2.1 Alcova confining unit within Chugwater aquifer and confining unit

Sweetwater Arch

The chemical composition of groundwater in the Alcova confining unit within of Chugwater aquifer and confining unit in the SA was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentrations (304 and 453 mg/L) indicated that the waters were fresh (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Alcova confining unit within of Chugwater aquifer and confining unit in the SA was suitable for most uses. No characteristics or constituents in the Alcova confining unit within of Chugwater aquifer and confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Alcova confining unit within of Chugwater aquifer and confining unit in the LM was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentrations (628 and 648 mg/L) indicated that the waters were fresh (**Appendix E5**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Alcova confining unit within of Chugwater aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS in both samples) and one constituent (sulfate in one sample) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards in both samples. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.20 Goose Egg confining unit and Goose Egg aquifer and confining unit

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

Physical characteristics

The Goose Egg confining unit and Goose Egg aquifer and confining unit consists of the Permian and Early Triassic Goose Egg Formation. Lithology of the Goose Egg Formation is highly variable and consists of a sequence of gypsum, anhydrite, limestone, dolomite, and moderately reddish-orange siltstone and shale (Maughan, 1964; Harshman, 1972). The formation has been divided into numerous members that differ by location. In places, the Opeche Shale and the Minnekahta Limestone are considered members of the Goose Egg Formation (Love and Christiansen, 1985, Sheet 2). The rocks were deposited in a marginal marine environment with high salinity and a warm arid climate, such as a vast shallow lagoon or tidal flat (Maughan, 1964). At the type location in Natrona County, the Goose Egg Formation is as much as 380-ft thick (Burk and Thomas, 1956).

Regionally, most investigators consider the Goose Egg Formation to be a confining unit; however, locally permeable discontinuous sandstones interbedded with low-permeability fine-grained lithologic units (shale, siltstone, limestone) occur throughout the formation. Consequently, the Goose Egg Formation, like the equivalent Phosphoria Formation and overlying Chugwater Group or Formation with very similar hydrogeologic characteristics, may be considered a sequence of rocks that regionally functions as both aquifer and confining unit (**Plates J, K, S, T, U**), depending upon location examined and the scale of the study. In the Granite Mountains and Shirley Basin, the Goose Egg aquifer and confining unit is overlain by the Chugwater aquifer and confining unit and underlain by the Casper aquifer (**Plate J**). The Goose Egg confining unit is overlain by the Sundance aquifer and underlain by the Hartville and Casper aquifers in the Hartville Uplift and Laramie Mountains (**Plate K**). In the Rawlins

Uplift, the Goose Egg aquifer and confining unit is overlain by the Chugwater aquifer and confining unit and underlain by the Tensleep aquifer (**Plate S**). The Goose Egg confining unit is overlain by the Chugwater confining unit and underlain by the Tensleep aquifer in the Sierra Madre, Medicine Bow Mountains, Saratoga Valley (**Plate T**). In the Hanna and Laramie Basins, the Goose Egg confining unit is overlain by the Chugwater confining unit and underlain by the Casper aquifer (**Plate U**).

Gypsum and anhydrite in interbeds and fractures in shales and siltstones of the Goose Egg Formation (and associated members, including the Opeche Shale) contribute to the overall confining characteristics of the unit. In the south-central edge of the Powder River Basin in the vicinity of Douglas, Garland (1996) found that gypsum and anhydrite enhanced overall ductility of the Goose Egg confining unit, allowing the unit to effectively confine and maintain hydraulic integrity of the underlying Casper aquifer in areas with widespread extensional fractures associated with Laramide folds and faults.

Most wells completed in the unit are low yielding (less than 20 gal/minute). Low-yielding wells are completed in the discontinuous and primarily confined sandstones of the Goose Egg confining unit and Goose Egg aquifer and confining unit throughout the PtRB. In addition, locally occurring fractured limestone interbeds also may be permeable (Richter, 1981a, Table IV-2). Stacy (1994) and Stacy and Huntoon (1994) noted that saturated limestone interbeds "form minor aquifers" within the Goose Egg confining unit in the Casper Mountain area at the northwestern flank of the Laramie Mountains. Larger well yields may be possible where secondary porosity and permeability (primarily fractures) have developed in areas with deformation (folds and faults) (Lowry et al., 1973; Richter, 1981a, Table IV-2; Stacy, 1994; Stacy and Huntoon, 1994). Wells completed in the unit are used primarily for stock purposes due to generally small well yield and poor groundwater quality. In the Rawlins Uplift area, Berry (1960, p. 16) reported that "small quantities of highly mineralized water" probably could be obtained from "permeable materials" in the Goose Egg Formation (identified as "undifferentiated rocks" of Permian age). Crist and Lowry (1972, p. 53) classified the Goose Egg Formation as a "low-yield aquifer" in Natrona County. Richter (1981a) defined the Goose Egg Formation as a regional leaky confining unit with locally permeable sandstones and fractured limestone interbeds in the general vicinity of the Laramie, Shirley, and Hanna Basins (**Plate K**). He also noted that the "locally scattered permeable and fractured limestone interbeds yield minor quantities (1 to 15 gal/min) of water to wells." Hydrogeologic data describing the Goose Egg confining unit and Goose Egg aquifer and confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Goose Egg confining unit and Goose Egg aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Goose Egg aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (86 percent of samples) and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 1,090 to 3,220 mg/L, with a median of 2,430 mg/L.

Concentrations of some characteristics and constituents in water from the Goose Egg aquifer and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon (in one of two samples analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L), strontium (in both of the samples analyzed for this constituent, the concentration exceeded the USEPA HAL of 4,000 μg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (100 percent; USEPA SMCL of 500 mg/L) and sulfate (100 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard 200 mg/L), TDS (86 percent; WDEQ Class II standard of 2,000 mg/L), boron (33 percent; WDEQ Class II standard of 750 μg/L), and chloride (14 percent; WDEQ Class II standard of 100 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Goose Egg confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as seven wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram C**). TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples) and remaining waters were moderately saline (**Appendix E5**; **Appendix G3**, **diagram C**; supplementary data tables). TDS concentrations ranged from 1,030 to 3,220 mg/L, with a median of 2,650 mg/L.

Concentrations of some characteristics and constituents in water from the Goose Egg confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic (TDS, 100 percent of samples analyzed for the constituent) and one constituent (sulfate, 100 percent) always exceeded aesthetic standards for domestic use.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. One characteristic (TDS, 92 percent of samples analyzed for the constituent) and one constituent (sulfate, 100 percent) in environmental water samples were measured at concentrations greater than agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.3.21 Dinwoody confining unit

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

Physical characteristics

The Dinwoody confining unit is composed of the Early Triassic Dinwoody Formation (**Plate J**). The Dinwoody Formation was described by Pipiringos and O'Sullivan (1978) as gray to olive-gray siltstone and shale with thin brown limestone beds near the base of this marine unit. In the Wind River Basin (WRB) and Granite Mountains, Richter (1981b, Table IV-1, and references therein) defined the Dinwoody Formation as a confining unit because the unit is composed of generally impermeable interbedded sandy dolomitic siltstone, calcareous sandstone, and thin dolomite and limestone; the investigator reported that the unit was as much as 250-ft thick. Few wells are known to be completed in the Dinwoody confining unit, and little information was located describing the physical and chemical hydrogeologic characteristics of the Dinwoody confining unit in the PtRB.

Chemical characteristics

The chemical composition of groundwater in the Dinwoody confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (6,600 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Dinwoody confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively) and State of Wyoming agricultural- and livestock-use standards (WDEQ Class II standards of 2,000 and 200 mg/L, respectively, and WDEQ Class III standards of 5,000 and 3,000 mg/L, respectively).

7.4 Paleozoic hydrogeologic units

Paleozoic hydrogeologic units (aquifers and confining units) are described in this section of the report. Paleozoic hydrogeologic units underlie much of the PtRB, but due to deep burial and highly mineralized groundwater unsuitable for most uses throughout most of their extent in the subsurface, they generally can be used only along mountain-basin margins where they crop out and are directly exposed at land surface or immediately downgradient in adjacent bordering structural basins where they occur at shallow depths below younger hydrogeologic units. In addition, permeability decreases and groundwater quality deteriorates rapidly downgradient from outcrop areas along the basin margins. Consequently, most wells in Paleozoic hydrogeologic units have been installed for oil and gas production, commonly at thousands of feet below land surface.

Permeability and groundwater circulation in Paleozoic hydrogeologic units is controlled by lithology, sedimentary structure and depositional environment, and tectonic structures such as folds and faults (Lundy, 1978; Huntoon and Lundy, 1979b; Thompson, 1979; Eisen et al., 1980; Richter, 1981a, b; Western Water Consultants, Inc., 1982, 1993, 1995; Davis, 1984; Huntoon, 1985, 1993; Wiersma, 1989; Younus, 1992; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; WWC Engineering, 2006a, b). The predominant lithologies of the lithostratigraphic units composing Paleozoic hydrogeologic units are sandstone, carbonates (limestone and dolomite), and shale. Primary porosity and intergranular permeability are much greater in the sandstones than in the carbonates and shale, where primary permeability is very low. Carbonate aquifers generally may be utilized only in areas where substantial secondary permeability is developed, most commonly in areas of structural deformation (for example, anticlines) and its associated faults and fractures.

As described herein and by earlier studies, water quality of aquifers contained in Paleozoic hydrogeologic units varies greatly (for example, Lundy, 1978; Huntoon and Lundy, 1979b; Thompson, 1979; Eisen et al., 1980; Richter, 1981a, b; Western Water Consultants, Inc., 1982, 1993, 1995; Davis, 1984; Huntoon, 1985, 1993; Wiersma, 1989; Mazor, 1990; Mazor et al., 1993; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; WWC Engineering, 2006a, b). Recharge to these units generally occurs where the aquifers crop out, although severing by faults near basin margins may disrupt basinward aquifer continuity and prevent much of this recharge from entering the aquifers downgradient from outcrop areas. Near recharge areas, water in these hydrogeologic units can be relatively fresh and may be suitable for most uses. This is where most domestic, stock, or public-supply wells are completed. Elsewhere, and with increasing depth (as indicated by co-produced oil and gas water samples) and as the water moves away from the outcrop, the water can have TDS concentrations several times that of seawater and is not suitable for most uses or is only marginally suitable for some uses. Where deeply buried, only oil or gas wells are completed in Paleozoic hydrogeologic units.

In parts of the PtRB, some Paleozoic hydrogeologic units possess sufficient hydraulic connection to comprise a regional aquifer system, generally referred to as the Paleozoic aquifer system (**Plates K, M**). The Paleozoic aquifer system is present in the Hartville uplift area, and along the flanks of the Casper Arch and Laramie Mountains and adjacent structural basins. The Paleozoic aquifer system includes some of the most important Paleozoic aquifers in the PtRB. Depending on location and depth, wells completed in the aquifers produce highly variable quantities and quality of water. Except near outcrops, where water-table (unconfined) conditions may be encountered, groundwater in the Paleozoic aquifer system is generally semiconfined or confined. With the exception of wells utilized for hydrocarbon (oil and gas) production, most wells completed in the Paleozoic aquifer system in the PtRB are located in or near outcrops along basin margins or along basin margins where drilling depths are shallow and economical, water quality and aquifer permeability are sufficient for intended uses, and the aquifer is located close to the population center.

7.4.1 Minnekahta Limestone

Present only in the Hartville Uplift and adjacent areas, the Permian Minnekahta Limestone consists of 0- to 40-ft thick yellow, pink, purple, and blue thin-bedded limestone and silty limestone (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). Locally, the Minnekahta Limestone may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). The Minnekahta Limestone is overlain by the Chugwater confining unit and underlain by the Opeche confining unit (**Plate K**). Little information is available describing the physical and chemical hydrogeologic characteristics of this lithostratigraphic unit, but the unit likely yields little to no water (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). No additional information was located describing the physical and chemical hydrogeologic characteristics of the Minnekahta Limestone in the PtRB, so additional description as part of this study was not possible.

7.4.2 Opeche confining unit

Present only in the Hartville Uplift and adjacent areas, the Opeche confining unit is composed of the Permian Opeche Shale (**Plate K**). The Opeche Shale consists of 0- to 120-ft thick red silty shale with some yellow to red sandstone; geodes and thin lenses of purple, red, and gray chert also are present (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965). Gypsum interbeds also may be present (Richter, 1981a, Table IV-2, p. 49, and references therein). Locally, the Opeche Shale may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). The Opeche confining unit is overlain by the Minnekahta Limestone and underlain by the Hartville aquifer (**Plate K**). The unit yields little to no water and is considered a confining unit (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Richter, 1981a, Table IV-2, p. 49).

7.4.3 Phosphoria aquifer and confining unit

The physical and chemical characteristics of the Phosphoria aquifer and confining unit in the PtRB are described in this section of the report.

Physical characteristics

Present only in the small part of the southeastern Wind River Structural Basin (WRB) contained within the PtRB, and Granite Mountains area, the Phosphoria aquifer and confining unit consists of the Permian Phosphoria Formation (also defined as the Park City Formation in some areas) (**Plate J**). The Phosphoria Formation ranges from 150 to 350 ft in thickness and is composed of interbedded, dense limestone, dolomite, siltstone, fine-grained sandstone, chert, and phosphatic shale (McKelvey et al., 1959; Richter, 1981b, Table IV-1, and references therein).

With the exception of petroleum exploration, very few wells are installed in the Phosphoria aquifer and confining unit. Development is limited to low-yield wells located along the basin margin where the formation crops out and drilling depths are shallow. Most information describing the formation composing the aquifer and confining unit comes from petroleum exploration.

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

Recharge to the Phosphoria aquifer and confining unit is likely from infiltration of precipitation and streamflow at outcrop areas and possibly interformational flow. Discharge from these units is likely to seeps, springs, streams, and interformational movement (Whitcomb and Lowry, 1968; Richter, 1981b). Well-yield and spring-discharge measurements and other hydraulic properties for the Phosphoria aquifer and confining unit are summarized on **Plate 3**; these data are from wells or drill-stem tests associated with petroleum exploration.

Chemical composition

Groundwater-quality data are presented and described for the Phosphoria aquifer and confining unit in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix F**).

Sweetwater Arch

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of 35 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, **diagram A**). TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (74 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F1**; **Appendix H1**, **diagram A;** supplementary data tables). TDS concentrations ranged from 1,480 to 21,800 mg/L, with a median of 4,880 mg/L.

Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; USEPA SMCL 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), chloride (37 percent; SMCL of 250 mg/L), and pH (22 percent above upper SMCL limit of 8.5 and 6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 200 mg/L), TDS (91 percent; WDEQ Class II standard of 2,000 mg/L), and chloride (83 percent; WDEQ Class II standard of 100 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (49 percent; WDEQ Class III standard of 5,000 mg/L), sulfate (40 percent; WDEQ Class III standard of 3,000 mg/L), pH (22 percent above upper WDEQ Class III limit of 8.5 and 6 percent below lower WDEQ Class III limit of 6.5), and chloride (3 percent; WDEQ Class III limit of 2,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 9 percent of produced-water samples.

Central Wyoming basins (south)

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram F**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples) and remaining waters ranged from slightly to very saline (**Appendix F2**; **Appendix H2**, **diagram F;** supplementary data tables). TDS concentrations ranged from 1,610 to 16,400 mg/L, with a median of 8,080 mg/L.

Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (91 percent), chloride (82 percent), and pH (11 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (91 percent of samples analyzed for the constituent), TDS (82 percent), chloride (82 percent), and pH (11 percent above upper limit). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (64 percent), chloride (36 percent), sulfate (27 percent), and pH (11 percent above upper limit). The State of Wyoming Class IV standard for TDS was exceeded in 27 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (22,500 mg/L) indicated that the water was very saline. Concentrations of some characteristics and constituents in water from the Phosphoria aquifer and confining unit in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural- and livestock-use standards. The State of Wyoming Class IV standard for TDS was exceeded in the produced-water sample.

7.4.4 Forelle Limestone

The physical and chemical characteristics of the Forelle Limestone in the PtRB are described in this section of the report.

Physical characteristics

The Late Permian Forelle Limestone is present throughout much of the PtRB (**Plates 1, 2; Plates K, M, T, U**). Most available information describing the geologic and hydrogeologic characteristics of the Forelle Limestone is from the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie. The Forelle Limestone consists of thinly bedded, gray, purple, tan, and purple limestone with locally interbedded thin red shales and siltstones; the formation may locally be brecciated and contain gypsum and anhydrite (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Howe, 1970; Lundy, 1978; Richter, 1981a). Locally, the Forelle Limestone may be considered a member of the Goose Egg Formation (Maughan, 1964; Love and Christiansen, 1985, Sheet 2). In the vicinity of the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie, the Forelle Limestone ranges from 9 to 25 ft in thickness (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Howe, 1970; Lundy, 1978). The Forelle Limestone is overlain by the Chugwater confining unit and underlain by the Satanka confining unit (**Plates K, M, T, U**).

The hydrogeology of the Forelle Limestone has not been evaluated in most locations of the PtRB. In the Laramie Basin, the Forelle Limestone often is grouped with the overlying Chugwater confining unit and underlying Satanka confining unit to collectively describe the hydrogeologic unit as one of several hydrogeologic units that confine the underlying Casper aquifer (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Mazor et al., 1993). Collectively, this group of hydrogeologic units that confine the underlying Casper aquifer were informally named the "Permo-Triassic redbeds" by Huntoon and Lundy (1979a) or "redbeds groundwater system/confining unit" by Mazor (1990) and Mazor et al. (1993) (**Plates K, U**) because of the distinctive red color of rocks (redbeds) common to these units. Consequently, the Forelle Limestone has been classified as a confining unit in some studies (**Plates K, U**) (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Richter, 1981a; Mazor, 1990; Younus, 1992; Mazor et al., 1993).

A few investigators have reported limited water-development potential for the Forelle Limestone in the Laramie Basin. In the city of Laramie, Morgan (1947) reported that a few wells completed in the Forelle Limestone produced water from the lower part of the formation. Similarly, Robinson (1956) observed that some wells on the western outskirts of Laramie obtained at least part of their water from the Forelle Limestone. In the southern Laramie Basin, Burritt (1962, p. 44) noted that the "Forelle may contain some water, but it is unimportant in the overall groundwater situation of the area," presumably because of the large quantities of water available from the Casper aquifer in the area.

More recently, WWC Engineering (2006a, p. 9-5 to 9-8) conducted a limited evaluation of the potential for the Forelle Limestone, in combination with the lower part of the Chugwater Formation and upper part of the underlying Satanka Shale, to provide water for irrigation of green spaces in Laramie city limits. The investigators reported on several wells in Laramie that obtain water either completely from the Forelle Limestone, or in combination with lower parts of the overlying Chugwater Formation. The investigators noted that recharge to the Forelle Limestone likely was from infiltration on outcrops and possibly vertical leakage from underlying hydrogeologic units with higher hydraulic heads (Casper aquifer and Satanka confining unit). The investigators (WWC Engineering, 2006a, p. 9-7) noted that the "primary discharge point for the Forelle Limestone occurs in the area between the south end of 30th Street and Huck Finn Pond" because "this area represents the lowest elevation of Forelle Limestone outcrops for over 13 miles to the south and 5 miles to the north." The investigators also noted discharge from the Forelle Limestone to Spring Creek, to springs that supply Huck Finn Pond, and to Warren Spring. Overall, based on the limited information obtained from this evaluation, the investigators concluded that the Forelle Limestone has potential for water-supply development, at least in some areas within Laramie city limits. Consequently, based on this limited information, the Forelle Limestone was tentatively classified herein as an aquifer only in the Laramie Basin (**Plate U**).

Chemical composition

Groundwater-quality data are presented and described for the Forelle Limestone in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Forelle Limestone in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (216 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Forelle Limestone in the SA was suitable for most uses. No characteristics or constituents in the Forelle Limestone approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Forelle Limestone in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentrations (73,400 and 76,900 mg/L) indicated that the waters were briny (TDS concentrations greater than 34,999 mg/L). Concentrations of some characteristics and constituents in water from the Forelle Limestone in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural- and livestock-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively, and WDEQ Class III standards of 5,000 mg/L, 2,000 mg/L, and 3, 000 mg/L, respectively) in both samples. The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

7.4.5 Satanka confining unit

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

Physical characteristics

The Satanka confining unit is composed of the Early Permian Satanka Shale, a lithostratigraphic unit present throughout much of the PtRB (**Plates 1, 2; Plates K, M, T, U**). Most available information describing the geologic and hydrogeologic characteristics of the Satanka Shale are from the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie. The Satanka Shale consists primarily of red shale and silty shale, siltstone, thin interbedded fine-grained sandstone beds, and locally occurring gypsum and anhydrite beds (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Benniran, 1970; Lundy, 1978). In the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of

Laramie, the Satanka Shale ranges from 140 to 338 ft in thickness (Morgan, 1947; Littleton, 1950b; Robinson, 1956; Burritt, 1962; Benniran, 1970; Lundy, 1978).

Many detailed studies of the Casper aquifer in the Laramie Basin and adjacent western flank of the Laramie Mountains near the city of Laramie have examined hydrogeologic characteristics of the overlying Satanka Shale; these studies clearly indicate the Satanka Shale is a confining unit, even in fractured areas (for example, Robinson, 1956; Burritt, 1962; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Despite being classified as a confining unit, sandstones interbedded in the Satanka confining unit in the Laramie Basin locally yield small quantities of water (often mineralized) to wells, commonly with artesian pressure (Littleton, 1950b; Robinson, 1956; Burritt, 1962; Lundy, 1978; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Burritt (1962) speculated that although shales and siltstones in the Satanka confining unit generally were impermeable, secondary porosity and permeability may be present in some areas due to fractures. Most wells completed in the Satanka confining unit are used for stock purposes (Littleton, 1950b; Robinson, 1956; Burritt, 1962). Although not studied in similar detail in other parts of the PtRB, it is likely that Satanka Shale hydrogeologic characteristics are similar to those reported for the Laramie Basin and adjacent Laramie Mountains.

In the Laramie Basin, the Satanka confining unit often is grouped with the overlying Forelle Limestone and Chugwater Formation to collectively describe the hydrogeologic units that confine the underlying Casper aquifer (Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Mazor, 1990; Mazor et al., 1993). Collectively, this group of hydrogeologic units that confine the underlying Casper aquifer were informally named the “Permo-Triassic redbeds” by Huntoon and Lundy (1979a) or “redbeds groundwater system/confining unit” by Mazor (1990) and Mazor et al. (1993) (**Plates K, U**) because of the distinctive red color (redbeds) common to these units. Well-yield measurements and other hydraulic properties for the Satanka confining unit are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Satanka confining unit in the PtRB. Groundwater quality is described in terms of a water’s suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix E**).

Sweetwater Arch

The chemical composition of groundwater in the Satanka confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (1,330 mg/L) indicated that the waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS; SMCL of 500 mg/L) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. One constituent (sulfate; WDEQ Class II standard of 200 mg/L) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Satanka confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from one spring. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (1,330 mg/L) indicated that the waters were slightly saline (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded aesthetic standards for domestic use. One constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Satanka confining unit in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 11 wells. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram D**). TDS concentrations were variable and indicated that most waters were fresh (91 percent of samples) and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram D**; supplementary data tables). TDS concentrations ranged from 194 to 2,370 mg/L, with a median of 906 mg/L.

Concentrations of some characteristics and constituents in water from the Satanka confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: radon, (67 percent of samples analyzed for the constituent exceeded the proposed USEPA MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L) and nitrate, (11 percent; MCL of 10 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (73 percent), sulfate (64 percent), and fluoride (14 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (64 percent of samples analyzed for the constituent) and TDS (9 percent; WDEQ Class II standards of 2,000 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.6 Casper aquifer

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

Physical characteristics

The Casper aquifer consists of saturated and permeable parts of the Permian and Pennsylvanian Casper Formation, and where present, saturated and permeable parts of the underlying Pennsylvanian Fountain Formation (**Plates J, K, M, T, U**). Both formations are present in the subsurface throughout much of the PtRB, but they crop out only along mountain-basin margins (**Plate 1**). In places, the upper part of the Casper Formation is equivalent to the Tensleep Sandstone and the lower part is equivalent to the Amsden Formation (Mallory, 1967). The Casper Formation is composed of thick sandstones interbedded with thin marine carbonates (limestone and dolomite) deposited in shallow marine, beach, and eolian environments (Pederson, 1953; Mallory, 1967; Benniran, 1970; Kirn, 1972; Huntoon, 1976; Lundy, 1978). The upper part of the Casper Formation generally consists of buff, tan, or reddish-brown, fine- to medium-grained, siliceous, well-cemented sandstone (Dobbin, Hoots, et al., 1929; Harshman, 1972; Lowry et al., 1973; Lundy, 1978). Arkosic sandstone beds in the lower part of the Casper Formation may be tongues of the Fountain Formation, which in the Laramie Basin is at its thickest extent in southern Albany County (Mallory, 1967; Lowry et al., 1973). The Casper Formation grades down to interbedded pink, purple, and gray dolomitic limestone and dolomite and tan to reddish-brown dolomitic sandstone, sandstone, and quartzite (Dobbin, Hoots, et al., 1929; Harshman, 1972; Lowry et al., 1973). Reported Casper Formation thickness varies substantially by location and ranges from about 500 to 1,200 ft (Pederson, 1953; Lowry and Crist, 1967; Mallory, 1967; Benniran, 1970; Kirn, 1972; Lowry et al., 1973; Huntoon, 1976; Lundy, 1978; Libra et al., 1981; Younus, 1992). The Fountain Formation consists of a 0- to 300-ft-thick sequence of reddish sandstone, arkose, and conglomerate, with red to purple arenaceous (sandy texture) shale and fine-grained sandstone near the base (Mallory, 1967; Kirn, 1972; Lundy, 1978). Mallory (1975) defined the Fountain Formation as a fan conglomerate from the ancestral Front Range and southern Pathfinder Uplift.

Depending on location, the Casper aquifer is confined from above by the Goose Egg, Opeche, Satanka, or Phosphoria confining units (**Plates J, K, M, T, U**). The Casper aquifer is underlain by different hydrogeologic units in different areas of the PtRB —the Amsden aquifer in the Granite Mountains Uplift and Shirley Basin areas (**Plate J**); the Madison aquifer, Englewood Limestone, or Fremont Canyon aquifer in the Hartville Uplift and the Laramie Mountains (**Plate K**); the Guernsey aquifer in the Denver-Julesburg Basin (**Plate M**); the Madison aquifer in the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas (**Plate T**); and the Madison aquifer in the Hanna and Laramie Basins (**Plate U**). Along part of the western flank of the Laramie Mountains near the city of Laramie, the Casper aquifer directly overlies igneous and metamorphic rocks comprising the Precambrian basal confining unit (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979).

Along parts of the flanks of the Laramie Mountains, in the Hartville Uplift, and in the Denver-Julesburg Basin, the Casper aquifer is interpreted by previous investigators to be hydraulically connected to other underlying and overlying Paleozoic hydrogeologic units, primarily through extensional fractures along the crests of folds, and thus, part of a regional aquifer system (**Plates K, M**) (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Weston Engineering, 2008). Several investigators identified this aquifer system as the "Paleozoic aquifer system" (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) and this name is retained herein (see last column in **Plates K and M**). In their study of the Paleozoic hydrogeologic units in the Casper Mountain area at the northwestern end of the Laramie Mountains, Stacy (1994) and Stacy and Huntoon (1994) identified the aquifer system as the "Madison aquifer" [see "Hydrogeologic role/unit of Stacy (1994) and Stacy and Huntoon, (1994)" column on **Plate K**]. In his study of Paleozoic hydrogeologic units and associated hydrogeologic units in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of the city of Douglas, Garland (1996) identified the aquifer system as the "Casper aquifer" [see "Hydrogeologic role/unit of Garland (1996)" column on **Plate K**].

Sandstone beds with varying primary (intergranular) permeability interbedded with low primary permeability marine carbonates and siltstones commonly comprise the Casper aquifer; the sandstone beds are considered a series of subaquifers confined by the carbonates where unfractured (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Western Water Consultants, Inc., 1995; Garland, 1996). In the Laramie Basin, the upper part of the Casper aquifer may be more permeable than the lower part (Morgan, 1947; Robinson, 1956). In many areas, the confined sandstone subaquifers are hydraulically connected by tectonic features (folds and faults) and associated extensional fracturing (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996). In addition to providing hydraulic connection of interbedded sandstone subaquifers, tectonically induced extensional fractures also can promote secondary permeability development in both the sandstones and carbonates (Davis, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Western Water Consultants, Inc., 1995; Garland, 1996). In fact, permeability of interbedded Casper aquifer limestones is likely negligible without secondary permeability development (Lundy, 1978; Huntoon and Lundy,

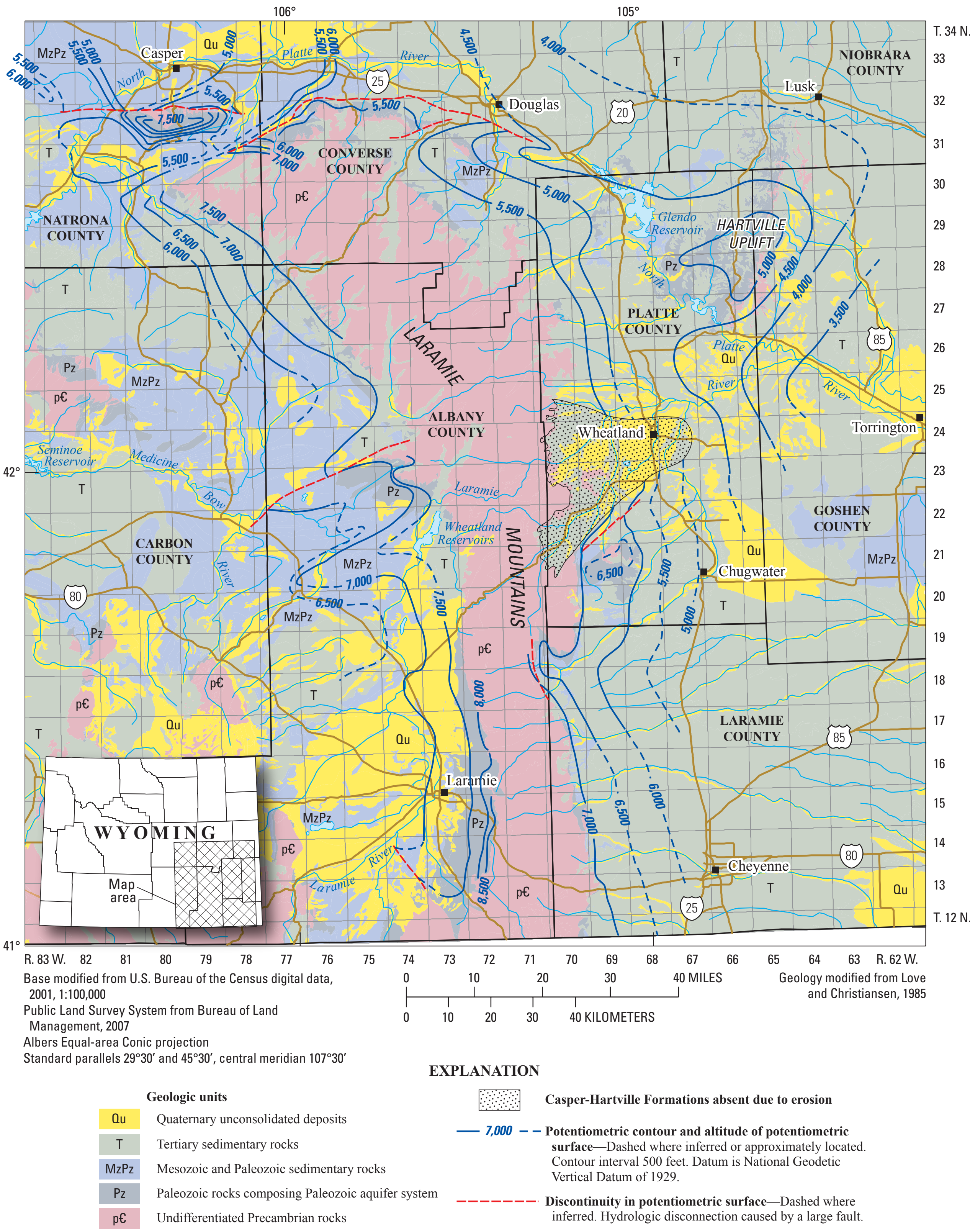


Figure 7-9. Generalized potentiometric surface for the Casper aquifer, southern Laramie Basin, Wyoming (modified from Chen, 1990, Figure 3.5).

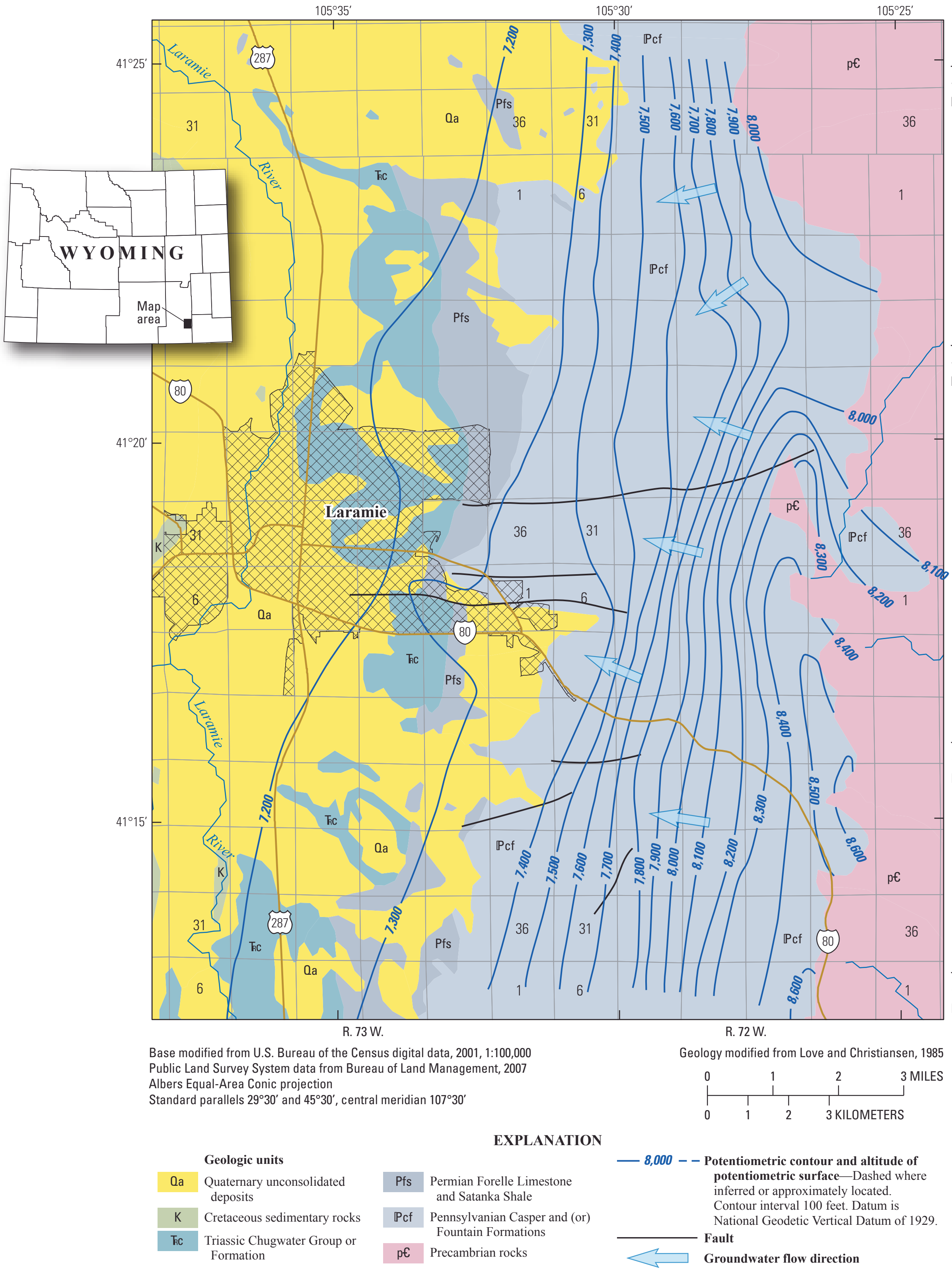


Figure 7-10. Generalized potentiometric surface for the Paleozoic aquifer system in southeastern Wyoming (modified from Western Water Consultants, Inc., 1982, Plate 3).

1979a; Garland, 1996). Joints, bedding-plane partings, and solution enlargement in the carbonate rocks contribute to secondary permeability in the Casper aquifer (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996, and references therein). Karstic development also likely enhances permeability in the Casper aquifer in some areas and also can provide a mechanism for vertical hydraulic connection between different parts of the aquifer or with other Paleozoic hydrogeologic units (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Permeability of Casper aquifer sandstones decreases basinward and with increasing depth in the Laramie Basin, at least partly because of increased cementation of pore space by anhydrite and dolomite and interbedded anhydrite (Garland, 1996). Similarly, Stacy (1994, p. 41) noted that Casper aquifer sandstone intergranular permeability in deeply buried subcrops in the Casper Mountain area "is locally being destroyed through recrystallization and cementation where groundwaters are supersaturated with respect to various minerals."

Vertical fracturing associated with faults can create vertical permeability pathways between the Casper aquifer and through overlying confining units (Lundy, 1978; Mazor, 1990; Mazor et al., 1993; Younus, 1992; Western Water Consultants, Inc., 1994, 1995, and references therein). In such areas, greater hydraulic heads in the Casper aquifer can result in upward circulation of groundwater through the fracture zones; natural mixing between groundwater from the Casper aquifer and overlying hydrogeologic units occurs in the fracture zones (Lundy, 1978; Mazor, 1990; Younus, 1992; Mazor et al., 1993; Western Water Consultants, Inc., 1994). Mixing of groundwater from the Casper aquifer with groundwater from overlying hydrogeologic units also occurs as a result of well-construction practices. In the vicinity of Laramie, wells have been constructed with well screens, perforations, or filter packs penetrating both the Casper aquifer and overlying Permian and Triassic hydrogeologic units (Lundy, 1978; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). Some wells are constructed without casing and are open to both the Casper aquifer and overlying Permian and Triassic hydrogeologic units. Consequently, these well-construction methods result in mixing of generally good quality groundwater from the Casper aquifer with generally poorer quality groundwater from overlying hydrogeologic units in the Laramie area (Lundy, 1978; Thompson, 1979; Mazor, 1990; Younus, 1992; Mazor et al., 1993). In addition, corroded or damaged well casing also may allow for mixing during well pumping (Mazor et al., 1993).

The Casper aquifer is used for stock, domestic, and public-supply purposes (TriHydro Corporation and Lidstone and Associates, Inc., 2007). The Casper aquifer is widely considered to be the only aquifer capable of supplying sufficient quantity and quality of water for public-supply and other uses to the city of Laramie and adjacent areas in the southern Laramie Basin on the western flank of the Laramie Mountains (for example, Western Water Consultants, Inc., 1995, p. 6-1); consequently, the aquifer has been studied extensively in this area (for example, Beckwith, 1937; Boos, 1940; Morgan, 1947; Robinson, 1956; Davis, 1976, 1984; Huntoon, 1976; Banner Associates, 1978; Lundy, 1978; Huntoon and Lundy, 1979a, b, and references therein; Thompson, 1979; Western Water Consultants, Inc., 1982, 1993, 1995; Morrison-Maierle, Inc., 1984a; Younus, 1992; Taboga, 2006; WWC Engineering, 2006a; Wittman Hydro Planning Associates, Inc., 2008). In other parts of the PtRB, Casper aquifer development has been relatively limited; however, exploration of the Casper aquifer and the Paleozoic aquifer system along the flanks of the Laramie Mountains and in the Hartville Uplift continues as the aquifer is considered to have substantial water-supply development potential (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996, and references therein; TriHydro Corporation and Lidstone and Associates, Inc., 2007).

Recharge to the Casper aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, intergranular pores, sinkholes, fractures, and faults (Beckwith, 1937; Lundy, 1978; Peterson, 1991; Younus, 1992; Stacy, 1994; Huntoon and Stacy, 1994; Garland, 1996; Taboga, 2006; Wittman Hydro Planning Associates, Inc., 2008). Recharge to the Casper aquifer on the western flank of the Laramie Mountains in the Laramie area has been estimated by several investigators (Lundy, 1978; Taboga, 2006; Wittman Hydro Planning Associates, Inc., 2008). Lundy (1978) estimated that recharge to the Casper aquifer averaged about 1.4 inches per year (about

8 to 13 percent of average annual precipitation). Using the Soil-Water Balance model (SWB), Wittman Hydro Planning Associates, Inc. (2008, p. 27) estimated recharge to the Casper aquifer averaged about 1 inch per year (about 10 percent of average annual precipitation) for the years 1981 to 2007. The investigators (Wittman Hydro Planning Associates, Inc., 2008, p. 27) also concluded that recharge to the Casper aquifer occurs primarily in late winter and early spring during snowmelt and that the amount and timing of snowpack are crucial to the amount of aquifer recharge; they also noted substantial recharge through faults, averaging about 9 percent of total recharge for the period of study. In the Casper Mountain area on the northwestern end of the Laramie Mountains, Stacy (1994) estimated that recharge to a fault-bound groundwater compartment of the Paleozoic aquifer system (defined as the Madison aquifer and composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) was about 22 percent of average annual precipitation. Garland (1996, Table 1) estimated groundwater recharge to different parts of the Casper aquifer (composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of Douglas to range from 7 to 36 percent of average annual precipitation.

Discharge from the Casper aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams. Major springs that discharge from the Casper aquifer generally are located near faults or steeply dipping folds. High-yielding fault-controlled springs provide a substantial percentage of the water used by the city of Laramie (Beckwith, 1937; Boos, 1940; Morgan, 1947; Robinson, 1956; Davis, 1976, 1984; Lundy, 1978; Huntoon and Lundy, 1979a, b, and references therein; Thompson, 1979; Western Water Consultants, Inc., 1982, 1993, 1995; Younus, 1992; Taboga, 2006; WWC Engineering, 2006a; Wittman Hydro Planning Associates, Inc., 2008). The primary anthropogenic sources of discharge are wells used to supply water (stock, domestic, public supply, and industrial wells) or extract energy resources (oil and gas wells).

Groundwater flow in the Casper aquifer is strongly affected by tectonic structures; fractured and brecciated zones and joints associated with tectonic structures (folds and faults) have substantially increased secondary porosity and permeability (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996; Taboga, 2006). Faults can act as both conduits and barriers to groundwater flow in the aquifer (Huntoon, 1976; Lundy, 1978; Huntoon and Lundy, 1979a; Thompson, 1979; Younus, 1992; Western Water Consultants, Inc., 1995; Garland, 1996; Taboga, 2006). In the Laramie Basin, high permeability zones in the vicinity of folds and faults "serve as collector structures and conduits for groundwater" and thus, "all major springs and the most productive wells that derive water from the Casper aquifer are located where the aquifer is highly fractured" (Thompson, 1979, p. 16).

Several potentiometric-surface maps have been constructed for parts of the Casper aquifer in the Laramie area (for example, Lundy, 1978; Davis, 1984, Figure 3; Chen, 1990, Figure 3.5; Younus, 1992; Western Water Consultants, Inc., 1995, Plate 6-2; WWC Engineering, 2006a, Plate 10-2). The potentiometric-surface map constructed by Chen (1990, Figure 3.5) is reproduced herein as **Figure 7-9**. All of these potentiometric-surface maps show groundwater flowing from the outcrop area along the western flank of the Laramie Mountains westward towards the interior of the Laramie Basin. In places, high permeability zones associated with tectonic features locally affect groundwater flow and are reflected in potentiometric-surface maps constructed for parts of the Casper aquifer (for example, Lundy, 1978; Western Water Consultants, Inc., 1995, Plate 6-2).

Several potentiometric-surface maps showing groundwater flow in the Paleozoic aquifer system in parts of the PtRB, including the Casper aquifer, have been constructed by previous investigators (Eisen et al., 1980; Libra et al., 1981, Figure IV-1; Western Water Consultants, Inc., 1982, Plate 3; Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in the Denver-Julesburg Basin and Hartville Uplift areas (Eisen et al., 1980; Libra et al., 1981), including the Casper aquifer (composed of the Casper and (or) Fountain Formations where present), is reproduced herein as **Plate 5**. The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in southeastern Wyoming, including the Casper aquifer where present, is reproduced herein as **Figure 7-10**. These three potentiometric-surface maps show groundwater flowing away from outcrop areas along the flanks of the Laramie Mountains and Hartville Uplift (areas of upland recharge) towards adjacent structural basin interiors.

In parts of the PtRB along mountain-basin margins, thrust faults with substantial vertical displacement sever Casper aquifer and Paleozoic aquifer system hydraulic continuity and thus, disrupt potentiometric-surface continuity (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (for example, see red dashed lines shown on **Figure 7-10**). Severing disrupts hydraulic continuity and segments or compartmentalizes the aquifer or aquifer system into discrete groundwater components or systems; hydraulic connection between the groundwater compartments is limited or absent, and each has a unique groundwater circulation system (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45).

Thompson (1979) constructed a steady-state groundwater-flow model of the Casper aquifer (composed of the Casper and Fountain Formations; **Plate K**) in the Laramie area. Custom-written by the author using finite-difference techniques, the groundwater-flow model was constructed to predict groundwater-level declines in the Casper aquifer caused by current and anticipated withdrawals in the study area. In addition, the effects of additional groundwater withdrawals on discharge to a fault-controlled spring used to supply water to the city of Laramie (Soldier Springs) were evaluated. After steady-state model development was completed, 17 different alternative groundwater-management scenarios were simulated.

Chemical characteristics

Chemical characteristics of both lithostratigraphic units (Casper and Fountain Formations) comprising the Casper aquifer in the PtRB are described in this section of the report. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

7.4.6.1 Casper aquifer (samples from the Casper Formation)

Sweetwater Arch

The chemical composition of groundwater in the Casper aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (75 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; supplementary data tables). TDS concentrations ranged from 276 to 1,880 mg/L, with a median of 396 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: gross alpha radioactivity (in the one sample analyzed for this constituent; USEPA MCL of 15 pCi/L), molybdenum (in one of two samples analyzed for this constituent; USEPA HAL of 40 μg/L), radium 226+228 (in the one sample analyzed for this constituent; MCL of 5 pCi/L), and uranium (in the one sample analyzed for this constituent; MCL of 30 μg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (38 percent; USEPA SMCL of 500 mg/L), iron (33 percent;

SMCL of 300 µg/L; and sulfate (25 percent; SMCL of 250 mg/L; supplementary data tables). Iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class II standard of 15 pCi/L), radium 226+228 (in the one sample analyzed for this constituent; WDEQ Class II standard of 5 pCi/L), and sulfate (25 percent; WDEQ Class II standard of 200 mg/L). Three constituents exceeded State of Wyoming livestock standards: gross alpha radioactivity (in the one sample analyzed for this constituent; WDEQ Class III standard of 15 pCi/L), and radium 226+228 (in the one sample analyzed for this constituent; WDEQ Class III standard of 5 pCi/L), and mercury (in the one uncensored sample analyzed for this constituent; WDEQ Class III standard of 0.05 µg/L). Mercury is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

The chemical composition of groundwater in the Casper aquifer in the SA also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (2,320 mg/L) indicated that the water was slightly saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS (WDEQ Class II standard of 2,000 mg/L), chloride (WDEQ Class II standard of 100 mg/L), and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Casper aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Individual constituent concentrations for this sample are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were fresh (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 340 to 9,650 mg/L, with a median of 3,060 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations exceeded health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (67 percent of samples analyzed for the constituent), chloride (67 percent), fluoride (67 percent; SMCL of 2 mg/L), and sulfate (67 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were TDS (67 percent), chloride (67 percent), sulfate (67 percent), and SAR (50 percent; WDEQ Class II standard of 8). Characteristics or constituents that exceeded State of Wyoming livestock standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

The chemical composition of groundwater in the Casper aquifer in the CBS was characterized and the quality evaluated on the basis of 55 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram G**). TDS concentrations were variable and indicated that most waters were moderately saline (58 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to briny (TDS concentrations greater than 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram G;** supplementary data tables). TDS concentrations ranged from 2,320 to 75,900 mg/L, with a median of 7,630 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (98 percent), chloride (91 percent), and pH (13 percent above upper SMCL limit of 8.5 and 4 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), sulfate (98 percent), and chloride (96 percent). Characteristics and constituents in produced-water samples measured at concentrations at greater than State of Wyoming livestock-use standards were TDS (65 percent), sulfate (40 percent; WDEQ Class III standard of 3,000 mg/L), chloride (38 percent), and pH (13 percent above upper WDEQ Class III limit of 8.5 and 4 percent below lower WDEQ Class III limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 38 percent of produced-water samples.

Medicine Bow Mountains

The chemical composition of groundwater in the Casper aquifer in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentrations (191 and 256 mg/L) indicated that the waters were fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer in the MBM was suitable for most uses. No characteristics or constituents in the Casper aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Casper aquifer in the MBM also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (4,170 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS, chloride, and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

Laramie Mountains

The chemical composition of groundwater in the Casper aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as 70 wells and 27 springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram E**). TDS concentrations were variable and indicated that most waters were fresh (95 percent of samples), and remaining waters were slightly saline (**Appendix E5**; **Appendix G3**, **diagram E**; supplementary data tables). TDS concentrations ranged from 102 to 1,520 mg/L, with a median of 214 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (67 percent of samples analyzed for the constituent exceeded proposed MCL of 300 pCi/L, whereas no samples exceeded the alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (13 percent), sulfate (8 percent), and pH (3 percent above upper limit).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the LM. One constituent in environmental water samples was measured at concentrations greater than agricultural-use standards was sulfate (11 percent). Concentrations of one characteristic were measured at greater than State of Wyoming livestock-use standards: pH (3 percent above upper limit).

Central Wyoming basins (north)

The chemical composition of groundwater in the Casper aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E6**. The TDS concentration (2,930 mg/L) indicated that the water was slightly saline (**Appendix E6**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards, the environmental water was suitable for domestic use. One characteristic (TDS) and two constituents (fluoride and sulfate) exceeded aesthetic standards for domestic use. One characteristic (TDS) and one constituent (sulfate) exceeded the State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Casper aquifer in the CBN also was characterized and the quality evaluated on the basis of seven produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**. TDS concentrations were variable and indicated that most waters were moderately saline (57 percent of samples), and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F5**; supplementary data tables). TDS concentrations ranged from 2,660 to 11,200 mg/L, with a median of 3,310 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (57 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (71 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (29 percent) and sulfate (29 percent). The State of Wyoming Class IV standard for TDS was exceeded in 14 percent of produced-water samples.

Great Plains

The chemical composition of groundwater in the Casper aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and six springs. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram I**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E7**; **Appendix G5**, **diagram I**; supplementary data tables). TDS concentrations ranged from 172 to 765 mg/L, with a median of 259 mg/L.

Concentrations of some characteristics and constituents in water from the Casper aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: arsenic (in two of three samples analyzed for this constituent; MCL of 10 μg/L). Concentrations of one characteristic and one constituent exceeded aesthetic standards for domestic use: TDS (10 percent) and sulfate (10 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. One constituent in environmental water samples measured at concentrations greater than agricultural-use standards was sulfate (10 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Casper aquifer in the GP also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F6**. The TDS concentration (3,680 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Casper aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use. TDS, chloride, and sulfate exceeded State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.6.2 Casper aquifer (samples from the Fountain Formation)

Medicine Bow Mountains

The chemical composition of groundwater in the Casper aquifer (samples from the Fountain Formation) in the MBM was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E4**. The TDS concentration (236 mg/L) indicated that the water was fresh (**Appendix E4**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer (samples from the Fountain Formation) in the MBM was suitable for most uses. No characteristics or constituents in the Fountain Formation approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Laramie Mountains

The chemical composition of groundwater in the Casper aquifer (samples from the Fountain Formation) in the LM was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E5**. The TDS concentration (224 mg/L) indicated that the water was fresh (**Appendix E5**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Casper aquifer (samples from the Fountain Formation) in the LM was suitable for most uses, but concentrations of one constituent exceeded health-based standards: radon (exceeded proposed and alternative MCL). No characteristics or constituents in the Casper aquifer (samples from the Fountain Formation) approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.4.7 Hartville aquifer

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

Physical characteristics

The Hartville aquifer consists of the Late Mississippian, Pennsylvanian, and Permian Hartville Formation, which is a lithostratigraphic unit present in the Denver-Julesburg Basin and Hartville Uplift areas (**Plates 1** and **2; Plate K**). The Hartville Formation is composed of carbonate rocks (limestone and dolomite), sandstone, shale, siltstone, and breccias; sandstones commonly are cherty and dolomitic (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Rapp et al., 1957; Morris and Babcock, 1960; Hoyt , 1962; Welder and Weeks, 1965; Sando and Sandberg, 1987; Wyoming Groundwater, LLC, 2009). Thickness ranges from 0 to 1,225 ft (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Rapp et al., 1957; Morris and Babcock, 1960; Hoyt, 1962; Welder and Weeks, 1965; Libra et al., 1981; Wyoming Groundwater, LLC, 2009). The Hartville Formation has been divided into many smaller lithostratigraphic units/intervals by different investigators (Condra and Reed, 1935; Condra et al., 1940; Love et al., 1949, 1953; Bates, 1955; Hoyt , 1962; Welder and Weeks, 1965; Mallory, 1967; Sando and Sandberg, 1987).

The Hartville aquifer is confined from above by the Opeche and Goose Egg confining units and underlain by the Guernsey aquifer (**Plate K**). In areas near Glendo, overlying Paleozoic and Mesozoic rocks have been eroded and the Cenozoic (Tertiary) White River aquifer/confining unit directly overlies the Hartville aquifer (Welder and Weeks, 1965; Wyoming Groundwater, LLC, 2009). Many studies (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) consider the Hartville aquifer to be part of the regional Paleozoic aquifer system where hydraulically connected to underlying and overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation; that interpretation was retained herein (**Plate K**).

The Hartville aquifer is used as a source of water for public-supply, stock, domestic, and irrigation purposes. The Hartville aquifer is used most heavily as a source of water in the vicinity of Glendo. The aquifer is used to supply water to the town of Glendo, and also is used to supply water for stock, domestic, and irrigation purposes in the area (Morrison-Maierle, Inc.; 1984b; Hibsman and Associates, 1990; Wyoming Groundwater, LLC, 2009).

Sandstones are the most productive zones within the Hartville aquifer (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Libra et al., 1981; Wyoming Groundwater, LLC, 2009). Most wells are completed in a productive white to yellow, fine- to medium-grained, subangular to subrounded sandstone as much as 100-ft thick or more present near the top of the unit known informally as the "Converse sand" (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen et al., 1980;

Libra et al., 1981; Western Water Consultants, Inc., 1982; Wyoming Groundwater, LLC, 2009). In addition to intergranular permeability, fractures reportedly increase Converse sand permeability in some areas (Wyoming Groundwater, LLC, 2009). Carbonate intervals within the Hartville aquifer generally are not productive or are much less productive than sandstones, but brittle carbonates in areas with secondary porosity and permeability ("interconnected fractures, cavities, and solution-enhanced features") may be productive (Wyoming Groundwater, LLC, 2009, p. 4-8). Intervals with secondary porosity and permeability development may be more common in breccias within the Hartville aquifer (Wyoming Groundwater, LLC, 2009). Wells completed in the Converse sand commonly are artesian (Rapp et al., 1957; Morris and Babcock, 1960; Welder and Weeks, 1965; Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; Wyoming Groundwater, LLC, 2009). Hydrogeologic data describing the Hartville aquifer in the PtRB, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Hartville aquifer in the Glendo area is from losing streams, overlying hydrogeologic units, and precipitation on outcrops (Welder and Weeks, 1965). Streamflow losses from Spring Creek recharge the Converse sand in some areas in the Glendo area. The North Platte River also provides "considerable recharge" to the Hartville aquifer in some areas in the Glendo area (Welder and Weeks, 1965, p. 29).

Discharge from the Hartville aquifer is both natural and anthropogenic. Natural sources of discharge from the Hartville aquifer in the Glendo area include discharge to the overlying White River aquifer/confining unit and to the alluvium in the North Platte River valley that is now covered by Glendo Reservoir (Welder and Weeks, 1965). In addition, Welder and Weeks (1965, p. 30) noted that discharge from the Hartville aquifer due to "evaporation, transpiration, and springs is probably negligible in the Glendo area." Wyoming Groundwater, LLC (2009, p. 4-9) noted that Buffalo Springs in the Glendo area "represents a local, rather than regional, discharge point" for the Hartville aquifer. Anthropogenic sources of discharge are the various wells completed in the aquifer, many of which are completed in the Converse sand.

Chemical characteristics

The chemical composition of groundwater in the Hartville aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E7**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G5**, **diagram J**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E7**; **Appendix G5**, **diagram J**; supplementary data tables). TDS concentrations ranged from 196 to 472 mg/L, with a median of 286 mg/L.

Concentrations of some characteristics and constituents in water from the Hartville aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of two constituents exceeded aesthetic standards for domestic use: manganese (20 percent) and iron (17 percent; USEPA SMCL of 300 μg/L). Dissolved manganese is not included in **Appendix E7** because values were too censored for the AMLE technique to calculate summary statistics. No characteristics or constituents exceeded State of Wyoming agricultural- or livestock-use standards.

The chemical composition of groundwater in the Hartville aquifer in the GP also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F6**. TDS concentrations were variable and indicated that most waters were moderately saline (67 percent of samples) and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix F6**; supplementary data tables). TDS concentrations ranged from 2,900 to 7,600 mg/L, with a median of 4,220 mg/L.

Concentrations of some characteristics and constituents in water from the Hartville aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent; SMCL of 500 mg/L), sulfate (100 percent; SMCL of 250 mg/L), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the GP. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 2,000 mg/L), sulfate (100 percent; WDEQ Class II standard of 200 mg/L), and chloride (67 percent; WDEQ Class II standard of 100 mg/L). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (33 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L).

7.4.8 Tensleep aquifer

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

Physical characteristics

The Tensleep aquifer consists of the saturated and permeable parts of the Middle and Late Pennsylvanian Tensleep Sandstone. Present at or near the land surface around uplifts in the PtRB (**Plate 1**), the Tensleep Sandstone is a white to buff, gray, and pink, fine-to medium-grained sandstone with some thin interbedded tan, white, gray, and pink, finely crystalline, dense limestone and dolomite (Dobbin, Bowen, and Hoots, 1929; Berry, 1960; Mallory, 1967, 1975). Carbonate beds (limestone and dolomite) commonly compose less than 20 percent of the formation (Mallory, 1967). The Tensleep Sandstone was deposited mostly as dunes, but also was deposited in fluvial, beach, and shallow marine environments (Maughan, 1967; Mallory, 1975). In his description of the formation in Wyoming, Mallory (1967) reported that the Tensleep Sandstone is best exposed in the Wind River and Bighorn Basins where reported thicknesses range from 50 to 350 ft. Berry (1960) reported a maximum thickness of 850 ft in the vicinity of the Rawlins Uplift. Reported thickness in the Wind River Basin (WRB) ranges from 200 to 600 ft (Richter, 1981b, Table IV-1). Welder and McGreevy (1966) reported a maximum thickness of about 800 ft in the Great Divide and Washakie Basins and adjacent areas. The Tensleep Sandstone is a source of oil, natural gas, and hydrogen sulfide in parts of the PtRB (De Bruin, 2002).

Depending on location, the Tensleep aquifer is confined from above by the Phosphoria aquifer and confining unit (Granite Mountains Uplift and Shirley Basin; **Plate J**), Goose Egg aquifer and confining unit (Rawlins Uplift; **Plate S**), or Goose Egg confining unit (Sierra Madre, Medicine Bow Mountains, and Saratoga Valley; **Plate T**). The Tensleep aquifer is underlain by the Amsden aquifer in most areas of the PtRB (**Plates J, S, T**). No regional confining unit separates the Tensleep aquifer from the underlying Amsden aquifer. In the vicinity of the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains, the Tensleep aquifer is underlain by the Madison aquifer (Johnson, 1994; Johnson and Huntoon, 1994).

The aquifer is used primarily as a source of water for domestic and stock purposes from wells located along basin margins where the Tensleep Sandstone crops out or is present at shallow depths. On the basis of well yields in the WRB, the uppermost 200 ft of the aquifer may be the most productive (Richter, 1981b). Confined conditions likely predominate, but unconfined (water-table) conditions are likely in outcrop areas of the Tensleep aquifer. Hydrogeologic data describing the Tensleep aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Early investigators (for example, Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of the Tensleep aquifer. Berry (1960, p. 15) noted that the Tensleep Sandstone was "known to yield water within" the Rawlins Uplift area. Collentine et al. (1981) defined the Tensleep Sandstone as a "major aquifer" in the Great Divide and Washakie Basins, including the adjacent Rawlins Uplift (**Plate S**). In addition, the investigators combined the aquifer with the aquifers in the underlying Amsden Formation and Madison Limestone into a regional aquifer system defined as the "Paleozoic aquifer system" (**Plate S**). Similarly, Richter (1981a) defined the formation as a "principal aquifer" in the general vicinity of the Laramie, Shirley, and Hanna Basins and adjacent areas (Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas) (**Plates S, T, U**). Because all or parts of the Casper Formation are considered stratigraphically equivalent to the Tensleep Sandstone, Richter (1981a; **Plate T**) referred to aquifers in both formations as the "Casper-Tensleep aquifer." In the WRB and the Granite Mountains area, Richter (1981b) defined the Tensleep Formation as an aquifer within a Paleozoic aquifer system identified as the "Tensleep aquifer system" (**Plate J**). Johnson (1994) and Johnson and Huntoon (1994) noted that the Tensleep aquifer is in hydraulic connection with the Madison aquifer through extensional fractures and faults in the vicinity of Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains. The USGS defined the formation as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Paleozoic aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

The Tensleep aquifer is composed of individual sandstone beds separated (confined) by low permeability beds of limestone and dolomite. Permeability in the Tensleep aquifer is both primary (intergranular) and secondary (fractures) (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994, and references therein). Fractures in these low permeability lithologies can provide hydraulic connection between the water-bearing layers. Much of what is known about the physical characteristics of the Tensleep aquifer in the PtRB and other areas of Wyoming commonly is inferred from detailed studies of Tensleep Sandstone characteristics in the Bighorn Basin (for example, Johnson, 1994; Johnson and Huntoon, 1994). On the basis of work conducted in the Bighorn Basin, porosity and permeability in the Tensleep Sandstone is thought to be primarily intergranular and to depend on the amount and type of primary and secondary cementation and recrystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966; Emmett et al., 1971; Mankiewicz and Steidtmann, 1979). Emmett et al. (1971) noted that highly crossbedded sandstones had lower permeabilities than regular bedded sandstones. Fractures and solution processes (in carbonate-rich zones) enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976; Richter, 1981a). Tensleep aquifer transmissivity decreases basinward (Bredehoeft, 1964). Secondary fracture porosity and permeability is common in folds and faults that deform the aquifer, and these locations, as reported in numerous studies in the Bighorn Basin, have the best potential for groundwater development (Jarvis, 1986; Spencer, 1986); by inference, the same potential likely exists in other parts of Wyoming, including the PtRB. In fact, Whitcomb and Lowry (1968) noted that the most productive wells in the Tensleep aquifer in the WRB are associated with local structures where fracturing has increased permeability, and Richter (1981b) noted that permeability in highly fractured parts of the aquifer along the Wind River Mountains might be several orders of magnitude greater than permeability in relatively undeformed areas such as the central part of the WRB.

Permeability of the Tensleep aquifer was examined in greater detail in part of the PtRB by Johnson (1994) and Johnson and Huntoon (1994). The investigators studied permeability of the aquifer in in the vicinity of Troublesome-Difficulty

Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains. As noted previously, the investigators reported permeability to be both intergranular and fracture enhanced. In addition, they noted that movement of water in the aquifer primarily is parallel to bedding, although fractures provide vertical hydraulic connection between permeable units when present. The investigators also noted that in some locations, permeability in the aquifer is enhanced by dissolutional enlargement of fractures and bedding planes.

Recharge to the Tensleep aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, fractures, intergranular pores, sinkholes, fractures, and faults (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). In addition, underlying aquifers such as the Madison aquifer are hydraulically connected to the Tensleep aquifer through extensional fractures in places and can provide interformational recharge to the Tensleep aquifer (Johnson, 1994; Johnson and Huntoon, 1994). Much of the recharge that enters through Tensleep aquifer outcrops is rejected due to basinward decreases in permeability/transmissivity and (or) hydraulic gradients; this rejected recharge is discharged to springs along the contact of the aquifer and overlying confining unit (Johnson, 1994; Johnson and Huntoon, 1994).

Discharge from the Tensleep aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). Numerous springs reportedly discharge “good quality water” (TDS generally less than 500 mg/L) from the Tensleep aquifer along the flanks of the Freezeout Mountains (Richter, 1981a). The primary anthropogenic sources of discharge are wells used to supply water (primarily stock and domestic) or extract energy resources (oil and gas wells).

Potentiometric-surface maps showing groundwater flow in the Tensleep aquifer have been constructed for parts of the aquifer in the PtRB. Collentine et al. (1981, Figure V-7, p. 71) constructed a generalized potentiometric-surface map for the Tensleep aquifer in the Great Divide Basin and the adjacent Rawlins Uplift. The map shows that groundwater generally flows away from the outcrop areas (and presumed source of recharge) along the flanks of the Great Divide Basin and the Rawlins Uplift. In the vicinity of the Troublesome-Difficulty Creek area between the Shirley Mountains and northern Hanna Basin and Freezeout Mountains, Johnson (1994) and Johnson and Huntoon (1994) showed that faults sever the Tensleep aquifer, disrupt hydraulic continuity, and compartmentalize the aquifer into three discrete groundwater systems; the groundwater compartments are hydraulically isolated from one another and each has a unique groundwater system with its own recharge, discharge, and groundwater flow characteristics (Johnson, 1994, Plate 3; Johnson and Huntoon, 1994, Plate 3). Some of these Tensleep aquifer groundwater compartments are inactive because they are completely bounded by normal and reverse faults, and thus, little to no groundwater flows into or out of the inactive groundwater system associated with these compartments (Johnson, 1994; Johnson and Huntoon, 1994).

Chemical characteristics

Groundwater-quality data are presented and described for the Tensleep aquifer in the PtRB. Groundwater quality is described in terms of a water’s suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Tensleep aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and 13 springs. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram B**). TDS concentrations were variable and indicated that most waters were fresh (TDS concentrations less than or equal to 999 mg/L) (88 percent of samples), and remaining waters were slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) (**Appendix E1**; **Appendix G1**, **diagram B**; supplementary data tables). TDS concentrations ranged from 165 to 2,210 mg/L, with a median of 260 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: radon (in three samples analyzed for this constituent, concentrations in two samples exceeded the proposed USEPA MCL of 300 pCi/L, and one of these concentrations exceeded the alternative MCL of 4,000 pCi/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: iron (33 percent; USEPA SMCL of 300 μg/L; supplementary data tables), manganese (33 percent; SMCL of 50 μg/L), TDS (25 percent; SMCL of 500 mg/L), sulfate (25 percent; SMCL of 250 mg/L), and fluoride (7 percent; SMCL of 2 mg/L). Dissolved iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were iron (33 percent of samples analyzed for the constituent; WDEQ Class II standard of 5,000 μg/L; supplementary data tables), sulfate (25 percent; WDEQ Class II standard of 200 mg/L), chloride (7 percent; WDEQ Class II standard of 100 mg/L), and TDS (6 percent; WDEQ Class II standard of 2,000 mg/L). Iron is not included in **Appendix E1** because values were too censored for the AMLE technique to calculate summary statistics. No characteristics or constituents exceeded State of Wyoming livestock standards.

The chemical composition of groundwater in the Tensleep aquifer in the SA also was characterized and the quality evaluated on the basis of 12 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, **diagram B**). TDS concentrations were variable and indicated that most waters were slightly saline (83 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F1**; **Appendix H1**, **diagram B;** supplementary data tables). TDS concentrations ranged from 1,060 to 6,250 mg/L, with a median of 1,780 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (100 percent), and chloride (33 percent; SMCL of 250 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), chloride (75 percent), and TDS (42 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (17 percent; WDEQ Class III standard of 5,000 mg/L) and sulfate (17 percent; WDEQ Class III standard of 3,000 mg/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Tensleep aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of two environmental water samples from wells. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentrations (276 and 950 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables).

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards in one sample and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents in the one sample analyzed for those constituents exceeded health-based standards: arsenic (MCL of 10 μg/L) and gross alpha radioactivity (MCL of 15 pCi/L). In one sample, one characteristic (TDS) and three constituents (fluoride, iron, and sulfate) exceeded aesthetic standards for domestic use. In one sample, two constituents exceeded the State of Wyoming agricultural-use standards: gross alpha radioactivity (WDEQ Class II standard of 15 pCi/L) and sulfate. One constituent (gross alpha radioactivity; WDEQ Class III standard of 15 pCi/L) exceeded State of Wyoming livestock standards in the one sample analyzed for that constituent.

The chemical composition of groundwater in the Tensleep aquifer in the CBS also was characterized and the quality evaluated on the basis of 20 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, **diagram H**). TDS concentrations were variable and indicated that most waters were moderately saline (55 percent of samples) and remaining waters ranged from slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L) to very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; **Appendix H2**, **diagram H;** supplementary data tables). TDS concentrations ranged from 1,300 to 23,300 mg/L, with a median of 7,480 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (95 percent), chloride (85 percent), and pH (6 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (95 percent of samples analyzed for the constituent), sulfate (95 percent), and TDS (90 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (75 percent), chloride (40 percent; WDEQ Class III standard of 2,000 mg/L), sulfate (30 percent), and pH (6 percent below lower WDEQ Class III limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 30 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Tensleep aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of 54 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram G**). TDS concentrations were variable and indicated that most waters were slightly saline (72 percent of samples), and remaining waters ranged from moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) to very saline (**Appendix F5**; **Appendix H3**, **diagram G**;

supplementary data tables). TDS concentrations ranged from 1,030 to 18,400 mg/L, with a median of 2,490 mg/L.

Concentrations of some characteristics and constituents in water from the Tensleep aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (94 percent), chloride (85 percent), and pH (4 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (94 percent of samples analyzed for the constituent), sulfate (94 percent), and TDS (78 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (9 percent), sulfate (9 percent), and pH (4 percent above upper WDEQ Class III limit of 8.5). The State of Wyoming Class IV standard for TDS was exceeded in 2 percent of produced-water samples.

7.4.9 Amsden aquifer

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

Physical characteristics

The Middle and Early Pennsylvanian and Late Mississippian Amsden Formation is tentatively identified as an aquifer (Amsden aquifer) (**Plates J, S, T**) in the PtRB. Since little is known about the Amsden aquifer in the PtRB, the descriptions of the unit's hydraulic characteristics are primarily based on those properties observed in the adjacent Wind River Basin (WRB) (Richter, 1981b). In the PtRB, the Amsden Formation is present at or near surface around the uplifts (**Plates 1 and 2**) or is deeply buried. The Amsden aquifer is overlain by the Tensleep or Casper aquifers and underlain by the Madison aquifer in the Granite Mountains Uplift and Shirley Basin (**Plate J**). In the Sierra Madre, Medicine Bow Mountains, Saratoga Valley, and Rawlins Uplift areas, the Amsden aquifer is overlain by the Tensleep aquifer and underlain by the Madison aquifer (**Plates S, T**).

The Amsden Formation in the WRB is composed of two stratigraphic sequences—a complex upper sequence of "nonresistant shale, dense dolomite, thin cherty limestone, and thin, resistant, fine-grained sandstone," and the basal Darwin Sandstone Member composed of a "fine- to medium-grained, crossbedded to massive, friable, porous sandstone" (Richter, 1981b, Table IV-1, from Keefer and Van Lieu, 1966). Reported thickness of the Amsden Formation ranges from 0 to 400 ft in the WRB (Richter, 1981b, Table IV-1).

In the rest of the PtRB, the Amsden Formation consists of three members: an upper Ranchester Limestone Member, a middle Horseshoe Shale Member, and a lower Darwin Sandstone Member (Mallory, 1967, 1975; Sando et al., 1975). The Ranchester Limestone Member is a sequence of gray, tan, pink, or purple, dense or finely crystalline, cherty dolomite, dolomitic limestone, and limestone (Mallory, 1967, 1975; Sando et al., 1975). They also described the Ranchester Limestone Member including some interbedded pink to dark-red to green shale or shaly limestone, and white to gray fine-to medium-grained sandstone, siltstone, and claystone. It is a marine deposit that is as much as 280-ft thick in Carbon County (Mallory, 1967, 1975; Sando et al., 1975). According to Mallory (1967, 1975) and Sando et al. (1975), the Horseshoe Shale Member is a red to purple or maroon shale, siltstone, and mudstone that is locally yellowish and light pinkish-gray with some beds and lenses of red fine-grained commonly calcareous sandstone, and silty, sandy, or argillaceous limestone. Sando et al. (1975) proposed that the Horseshoe Shale Member was deposited in a lagoonal environment. It is as much as 150-ft thick in Carbon County (Mallory, 1967; Sando et al., 1975). The Darwin Sandstone Member is a gray, white, cream, to salmon-colored fine-to medium-grained quartz sandstone with silica and locally calcite cement (Mallory, 1967; Sando et al., 1975). The sandstone was deposited in a complicated network of dunes, beaches, and bars during a dominantly eastward transgressing shoreline following the drowning of a fluvial system that was associated with the karst topography of an eroding Madison Limestone (Mallory, 1967; Sando et al., 1975). Sando and Sandberg (1987, Figure 5) considered the Horseshoe Shale Member of the Amsden Formation in the southern Wind River Mountains to be equivalent to the Darwin Sandstone Member of the Amsden Formation in the Rawlins Uplift and Ferris Mountains areas. The investigators (Sando and Sandberg, 1987, Figure 5) considered the "Darwin Sandstone Member" to be part of the Casper Formation in the northern Laramie Mountains and part of the Hartville Formation in the Hartville Uplift area.

Although tentatively classified as an aquifer herein, relatively little is known about the hydrogeology of the Amsden Formation in the PtRB. In the Rawlins Uplift area, Berry (1960, p. 15), stated that little was known about the water-bearing properties of the Amsden Formation, and that the formation likely "would yield very little water" because of low permeability rocks. Welder and McGreevy (1966) stated that "groundwater possibilities not known, but probably poor" in the Great Divide and Washakie Basins. Similarly, Collentine et al. (1981, Table V-1, p. 46) defined the Amsden Formation as an "aquitard" between the Tensleep aquifer and underlying Madison aquifer in the Great Divide and Washakie Basins and Rawlins Uplift (**Plate S**), and stated that the "unit probably has poor water-bearing potential due to predominance of fine-grained sediments." Saulnier (1968) reported locally permeable zones in the Amsden Formation in the north flank of the Medicine Bow Mountains and Pass Creek Basin areas. Permeability in some parts of the Amsden Formation may be larger than in other parts. In the WRB, permeability in the Darwin Sandstone is present due to joints and partings between bedding planes, and permeability of both the upper and basal sequences may be substantially enhanced where fractured (Richter, 1981b). Richter (1981b, Table IV-1, p. 52) noted that water in the Amsden aquifer in the WRB is confined and that well yields ranged from "between 1 to several hundred gallons per minute." Essentially no development of the aquifer has occurred in the PtRB because higher yields can be obtained from wells completed in other Paleozoic aquifers, often at shallower depth. Consequently, almost no study of the aquifer has occurred and no quantitative hydrogeologic information could be located for the Amsden aquifer in the PtRB.

Chemical characteristics

Groundwater-quality data are presented and described for the Amsden aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendix F**).

Sweetwater Arch

The chemical composition of groundwater in the Amsden aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (1,300 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Amsden aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards.

There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively). One constituent (sulfate) exceeded State of Wyoming agricultural-use standards (WDEQ Class II standard of 200 mg/L). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Amsden aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (67 percent of samples) and remaining waters were very saline (TDS concentrations ranging from 10,000 to 34,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 6,480 to 15,700 mg/L, with a median of 9,450 mg/L.

Concentrations of some characteristics and constituents in water from the Amsden aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent; SMCL of 250 mg/L), and sulfate (100 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent; WDEQ Class II standard of 2,000 mg/L), chloride (100 percent; WDEQ Class II standard of 100 mg/L), and sulfate (100 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were TDS (100 percent; WDEQ Class III standard of 5,000 mg/L), chloride (67 percent; WDEQ Class III standard of 2,000 mg/L), and sulfate (33 percent; WDEQ Class III standard of 3,000 mg/L). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in 33 percent of produced-water samples.

Central Wyoming basins (north)

The chemical composition of groundwater in the Amsden aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F5**. The TDS concentration (3,540 mg/L) indicated that the water was moderately saline. Concentrations of some characteristics and constituents in water from the Amsden aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use and State of Wyoming agricultural-use standards. No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.10 Madison aquifer

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

Physical characteristics

The permeable parts of the Early and Late Mississippian Madison Limestone comprise the Madison aquifer. The Madison Limestone is at or near land surface around most uplifts of the PtRB (**Plate 2**). The Madison Limestone is present in the subsurface throughout much of the PtRB, with the exception of the Denver-Julesburg Basin. Most of the Madison Limestone is pink, purple, and gray limestone, dolomitic limestone and dolomite, with some sandy beds and lenses or beds of greenish-gray to brownish-gray chert (Berry, 1960; Harshman, 1972; Mallory, 1979; Sando and Sandberg, 1987). Units that overlie the Madison Limestone were deposited on well-developed karst topography (Harshman, 1972; Sando et al., 1975). The Madison Limestone is a shallow to moderately deep marine deposit that ranges from 0- to about 500-ft thick (Maughan, 1963; Mallory, 1979). The Madison Limestone has been divided into different members in different parts of the PtRB (for example, Maughan, 1963; Harshman, 1972; Mallory, 1979; Sando and Sandberg, 1987). The Madison Limestone is locally cavernous in outcrop. In the Rawlins area, the basal Madison Limestone is a dark brown or dark reddish-brown arkosic sandstone and conglomerate that grades to a fine-grained red to brown sandstone (Berry, 1960; Maughan, 1963; Harshman, 1972; Mallory, 1979). Sando and Sandberg (1987) suggested that parts of this sandstone may be the Englewood Formation and (or) Fremont Canyon Sandstone. Macke (1993, p. M93) suggested that this actually is the Cambrian-age Flathead Sandstone. This sandstone was deposited in nearshore marine environments around the ancestral Front Range that was an emergent lowland at this time (Mallory, 1979; Sando and Sandberg, 1987).

Depending on location, the Madison aquifer is overlain by the Amsden aquifer in the Granite Mountains Uplift and Shirley Basin (**Plate J**), Rawlins Uplift (**Plate S**), and the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley (**Plate T**). The Madison aquifer is overlain by the Casper aquifer in the Hartville Uplift and Laramie Mountains (**Plate K**) and Hanna and Laramie Basins (**Plate U**). No regional confining unit separates the Madison aquifer from the overlying Amsden and Casper aquifers. The Madison aquifer is underlain by different hydrogeologic units in different areas of the PtRB —the Gallatin confining unit in the Granite Mountains Uplift and Shirley Basin areas (**Plate J**); the Englewood Limestone in the Hartville Uplift and the Laramie Mountains (**Plate K**); the Flathead aquifer in the Rawlins Uplift (**Plate S**); the Precambrian basal confining unit in the Sierra Madre, Medicine Bow Mountains, and Saratoga Valley areas (**Plate T**); and the Fremont Canyon Sandstone/aquifer in the Hanna and Laramie Basins (**Plate U**).

The Madison Limestone is considered an aquifer by most investigators throughout most of PtRB (**Plates J, K, T, U**). Collentine et al. (1981) defined the Madison Limestone as a "major aquifer" in the Great Divide and Washakie Basins. In addition, the investigator combined the aquifer with aquifers in the overlying Amsden Formation and Tensleep Sandstone and underlying undifferentiated Cambrian rocks into a regional aquifer system defined as the "Paleozoic aquifer system." In contrast, Richter (1981a) did not define the formation as an aquifer in the general vicinity of the Laramie, Shirley, and Hanna Basins. Detailed studies of the Madison Limestone in the vicinity of fault-severed basin-mountain margins in parts of the PtRB all classified the formation as an aquifer (Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). The USGS defined the Madison Limestone as a "principal aquifer" (Whitehead, 1996) and referred to the aquifer as part of the "Paleozoic aquifers" category on the national principal aquifers map (U.S. Geological Survey, 2013).

Porosity and permeability in the Madison aquifer is primarily secondary, well-developed in places, and is attributed to solution-enhanced fractures, joints, bedding planes, and caverns (Berry, 1960; Whitcomb and Lowry, 1968; McGreevy et al., 1969; Boner et al., 1976; Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Primary permeability is very low to nonexistent because of the dense and finely crystalline structure of the carbonates composing the aquifer (Boner et al., 1976; Richter, 1981a; Johnson, 1994;

Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Without development of secondary permeability, well yields in the Madison aquifer are likely to be relatively small (Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). The most productive (permeable) parts of the Madison aquifer are in areas with substantial fractures, karstic zones, and cavernous zones in karstic areas (Richter, 1981a; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Garland (1996) noted that Madison aquifer carbonates in the vicinity of the southern Powder River Basin were "generally tight" but "possess permeability along bedding-plane partings." Aquifer transmissivity is much higher in the basin-mountain margin than in the respective adjacent structural basin and decreases basinward and with increasing depth (Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996).

Along parts of the flanks of the Laramie Mountains, in the Hartville Uplift, and in the Denver-Julesburg Basin, the Madison aquifer is interpreted by previous investigators to be hydraulically connected to other underlying and overlying Paleozoic hydrogeologic units, primarily through extensional fractures along the crests of folds, and thus, part of a regional aquifer system (**Plates K, M**) (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996; Weston Engineering, 2008). Several investigators identified this aquifer system as the "Paleozoic aquifer system" (Eisen et al., 1980; Western Water Consultants, Inc., 1982) and this name is retained herein (see last column in **Plates K and M**). In their study of the Paleozoic hydrogeologic units in the Casper Mountain area at the northwestern end of the Laramie Mountains, Stacy (1994) and Stacy and Huntoon (1994) identified the aquifer system as the "Madison aquifer" [see "Hydrogeologic role/unit of Stacy (1994) and Stacy and Huntoon, (1994)" column on **Plate K**]. In his study of Paleozoic hydrogeologic units and associated hydrogeologic units in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of the city of Douglas, Garland (1996) identified the aquifer system as the "Casper aquifer" [see "Hydrogeologic role/unit of Garland (1996)" column on **Plate K**].

Several potentiometric-surface maps showing groundwater flow in the Paleozoic aquifer system in parts of the PtRB, including the Madison aquifer, have been constructed by previous investigators (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). The potentiometric-surface map showing groundwater flow in the Paleozoic aquifer system in southeastern Wyoming, including the Madison aquifer where present, is reproduced herein as **Figure 7-10** and generally shows groundwater flowing away from outcrop areas along the flanks of the mountains (areas of upland recharge) towards adjacent structural basin interiors. In parts of the PtRB along mountain-basin margins, thrust faults with substantial vertical displacement sever Madison aquifer and Paleozoic aquifer system hydraulic continuity and thus, disrupt potentiometric-surface continuity (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (for example, red dashed lines shown on **Figure 7-10**). Severing disrupts hydraulic continuity and segments or compartmentalizes the aquifer or aquifer system into discrete groundwater components or systems; limited to no hydraulic connection exists between the groundwater compartments, and each has a unique groundwater circulation system (Stacy, 1994, Figures 7, 36, and 37; Stacy and Huntoon, 1994, Figures 7, 36, and 37; Garland, 1996, Figures, 40, 41, 42, and 45). Isolated groundwater systems commonly develop in both the hanging and footwall blocks (Stacy, 1994; Stacy and Huntoon, 1994).

Although potentially highly productive in places, the Madison aquifer has not been extensively developed in the PtRB. Most wells completed in the Madison aquifer are located along the basin margin where the hydrogeologic unit crops out or is present at relatively shallow depth. Water in the aquifer is generally confined except in the vicinity of outcrops, and some wells may be artesian. Hydrogeologic data describing the Madison aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Recharge to the Madison aquifer occurs primarily by direct infiltration of precipitation, runoff, and ephemeral and perennial streamflow losses on outcrops, including through joints, fractures, intergranular pores, sinkholes, fractures, and faults (Boner et al., 1976; Collentine et al., 1981; Richter, 1981a, b; Peterson, 1991; Glass and Sultz, 1992; Johnson, 1994; Johnson and Huntoon, 1994; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Recharge from streamflow losses on Madison aquifer outcrops is likely substantial in some areas, as indicated by losses determined using streamflow measurements in the Little Box Elder and Cottonwood Creek areas (Boner et al., 1976; Peterson, 1991; Glass and Sultz, 1992; Garland, 1996). Peterson (1991) indicated that much of the streamflow loss along Little Box Elder Creek was lost to sinkholes in karstic parts of the Madison aquifer. Garland (1996) reported streamflow losses along Sawmill Creek, but he indicated that the amount of water lost cannot be quantified due to alluvium in the area. Garland (1996, Table 1) estimated groundwater recharge ranged from 7 to 36 percent of average annual precipitation to different parts of the Casper aquifer (composed of the Casper and Madison Formations and Fremont Canyon Sandstone; **Plate K**) in the northeastern flank of the Laramie Mountains in the south-central edge of the Powder River Basin in the vicinity of Douglas.

Discharge from the Madison aquifer is both natural and anthropogenic. Groundwater naturally discharges through seeps, springs, interformational movement, and gaining streams (Collentine et al., 1981; Richter, 1981a, b; Johnson, 1994; Johnson and Huntoon, 1994). Garland (1996) estimated that as much as 23 percent of the discharge observed in the Douglas City Spring was derived from recharge from direct infiltration of precipitation and snowmelt on Madison and Casper aquifer outcrops. Much of the recharge that enters through Madison aquifer outcrops may be rejected due to basinward decreases in permeability/transmissivity and (or) hydraulic gradients; this rejected recharge is discharged to springs along the contact of the aquifer and overlying confining unit (Johnson, 1994; Johnson and Huntoon, 1994; Garland, 1996). In addition, groundwater in the Madison aquifer is discharged to topographically low areas where the aquifer crops out or to the land surface in areas where hydraulically connected to the aquifer by vertical extensional fractures (Garland, 1996). The primary anthropogenic sources of discharge are wells used to supply water (stock and domestic) or extract petroleum.

Chemical characteristics

Groundwater-quality data are presented and described for the Madison aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Madison aquifer in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentrations (170 and 233 mg/L) indicated that the waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Madison aquifer in the SA was suitable for most uses, but concentrations of one constituent exceeded health-based standards: radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). No characteristics or constituents in the Madison aquifer approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

The chemical composition of groundwater in the Madison aquifer in the SA also was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentrations (1,090 and 1,290 mg/L) indicated that the water was slightly saline (TDS concentrations ranging from 1,000 to 2,999 mg/L). Concentrations of some characteristics and constituents in water from the Madison aquifer in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only two produced-water samples, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS and sulfate exceeded aesthetic standards for domestic use in both samples (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively). Chloride and sulfate exceeded State of Wyoming agricultural-use standards in both samples (WDEQ Class II standards of 100 mg/L and 200 mg/L, respectively). No characteristics or constituents exceeded State of Wyoming livestock standards.

Central Wyoming basins (south)

The chemical composition of groundwater in the Madison aquifer in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of three produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,140 to 7,070 mg/L, with a median of 2,880 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), chloride (100 percent; SMCL of 250 mg/L), sulfate (67 percent), and pH (33 percent above upper SMCL limit of 8.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were TDS (100 percent of samples analyzed for the constituent; WDEQ Class II standard of 2,000 mg/L), chloride (100 percent), and sulfate (67 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (33 percent above upper WDEQ Class III limit of 8.5), TDS (33 percent; WDEQ Class III standard of 5,000 mg/L), and chloride (33 percent; WDEQ Class III standard of 2,000 mg/L).

Laramie Mountains

The chemical composition of groundwater in the Madison aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and three springs. Summary statistics calculated for available constituents are listed in **Appendix E5**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E5**; supplementary data tables). TDS concentrations ranged from 219 to 257 mg/L, with a median of 231 mg/L. On the basis of the characteristics and constituents analyzed, the quality of water from the Madison aquifer in the LM was suitable for most uses. No characteristics or constituents in the Madison aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (north)

The chemical composition of groundwater in the Madison aquifer in the central Wyoming basins (north) (CBN) was characterized and the quality evaluated on the basis of environmental water samples from as many as six wells. Summary statistics calculated for available constituents are listed in **Appendix E6**. TDS concentrations were variable and indicated that most waters were moderately saline (50 percent of samples), and remaining waters ranged from fresh to slightly saline (**Appendix E6**; supplementary data tables). TDS concentrations ranged from 732 to 5,680 mg/L, with a median of 3,150 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: arsenic (in the one sample analyzed for this constituent; USEPA MCL of 10 μg/L) and fluoride (50 percent; MCL of 4 mg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), iron (in the one sample analyzed for this constituent; SMCL of 300 μg/L), manganese (in the one sample analyzed for this constituent; SMCL of 50 μg/L), sulfate (100 percent), chloride (83 percent), and fluoride (75 percent; SMCL of 2 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were manganese (in the one sample analyzed for this constituent; WDEQ Class II standard of 200 μg/L), sulfate (100 percent), TDS (83 percent), chloride (83 percent), SAR (33 percent; WDEQ Class II standard of 8), and boron (25 percent; WDEQ Class II standard of 750 μg/L). Concentrations of one characteristic and one constituent were measured at greater than State of Wyoming livestock-use standards: TDS (17 percent) and sulfate (17 percent; WDEQ Class III standard of 3,000 mg/L).

The chemical composition of groundwater in the Madison aquifer in the CBN was characterized and the quality evaluated on the basis of 10 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, **diagram H**). TDS concentrations were variable and indicated that most waters were moderately saline (60 percent of samples), and remaining waters were slightly saline (**Appendix F5**; **Appendix H3**, **diagram H;** supplementary data tables). TDS concentrations ranged from 1,220 to 7,770 mg/L, with a median of 3,160 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the CBN approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. There were no produced-water constituent analyses that could be compared with health-based standards. Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent of samples analyzed for the constituent), sulfate (90 percent), chloride (70 percent), and pH (38 percent below lower SMCL limit of 6.5).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBN. Characteristics and constituents in produced-water samples measured at concentrations greater than agricultural-use standards were chloride (100 percent), sulfate (90 percent), and TDS (70 percent). Characteristics and constituents in produced-water samples measured at greater than State of Wyoming livestock-use standards were pH (38 percent below lower WDEQ Class III limit of 6.5), TDS (20 percent), and sulfate (20 percent).

Great Plains

The chemical composition of groundwater in the Madison aquifer in the Great Plains (GP) was characterized and the quality evaluated on the basis of environmental water samples from as many as three wells. Summary statistics calculated for available constituents are listed in **Appendix E7**. TDS concentrations were variable and indicated that most waters were slightly saline (67 percent of samples), and remaining waters were fresh (**Appendix E7**; supplementary data tables). TDS concentrations ranged from 843 to 1,250 mg/L, with a median of 1,160 mg/L.

Concentrations of some characteristics and constituents in water from the Madison aquifer in the GP approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards: lead (the concentration in one of two samples analyzed for this constituent exceeded the USEPA MCL (action level) of 15 μg/L). Concentrations of several characteristics and constituents exceeded aesthetic standards for domestic use: TDS (100 percent), manganese (100 percent), sulfate (100 percent), aluminum (the concentration in one of two samples analyzed for this constituent exceeded the lower SMCL limit of 50 μg/L and also exceeded the upper SMCL limit of 200 μg/L), fluoride (50 percent), and iron (50 percent).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the CBS. Characteristics and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent of samples analyzed for the constituent), manganese (50 percent), and chloride (33 percent). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.4.11 Guernsey aquifer

The Guernsey aquifer is composed of the Early Mississippian Guernsey Formation, a lithostratigraphic unit present only in the Denver Julesburg Basin and Hartville Uplift areas (**Plates 1 and 2**). The Guernsey aquifer is overlain by the Hartville aquifer and underlain by the Englewood Formation/Limestone (**Plate K**). Morris and Babcock (1960, Table 1, p. 22) described the Guernsey Formation in Platte County as a 0- to 200-ft or more thick "hard gray moderately cherty coarsely-bedded limestone; thin-bedded slabby very fine-grained hard, brittle, silty, purple to gray dolomite; and hard dolomitic purple shale and siltstone." Rapp et al. (1957) informally split the Guernsey Formation in Goshen County into upper and lower units. The upper unit was described as a 0- to 135-ft or more thick "hard gray moderately cherty coarsely bedded limestone," whereas the unit below is a 0 to 65 ft or more thick "thin-bedded slabby very fine-grained hard, brittle, silty, purple to gray dolomite interbedded with hard dolomitic purple shale and siltstone" with "about 4 ft of pink arkose near the base" (Rapp et al., 1957, unnumbered table, p. 23). Welder and Weeks (1965, Table 1) reported a thickness of 150 to 250 ft for the Guernsey Formation in the Glendo area; the investigators described the unit as a gray, fine- to coarse-grained cherty limestone interbedded with chalky dolomite, with purple to gray, fine-grained, thin-bedded, brittle dolomite in the lower part and an arkose at the base.

Lithostratigraphy of the Guernsey Formation was reinterpreted by Sando and Sandberg (1987). The investigators concluded that the formation name was not valid and that the "Guernsey Formation" was a "superfluous name." The investigators assigned rocks formerly belonging to the basal part of the Guernsey Formation to the newly defined Fremont Canyon Sandstone and Englewood Formation; furthermore, they argued that the rest of the Guernsey Formation should be assigned to the "Big Goose and Little Tongue Members" of the Madison Limestone. Subsequently, the statewide Phanerozoic chart for Wyoming (Love et al., 1993) retained Sando and Sandberg's establishment of the Fremont

Canyon Sandstone and Englewood Formation, but apparently did not accept reassignment of the rest of the rocks formerly assigned to the Guernsey Formation to the "Big Goose and Little Tongue Members" of the Madison Limestone. Consequently, all three lithostratigraphic units currently are recognized in the PtRB (Love et al., 1993).

Deeply buried in most areas, very few wells are installed in the Guernsey Formation and thus, very little information describing physical and chemical characteristics of this unit is available. The few well-yield and spring-discharge measurements available for the Guernsey aquifer are summarized on **Plate 3**. Because of historical and current use of "Guernsey Formation" for at least some of these rocks, convention in this study was to retain previous lithostratigraphic assignments for the few wells or springs with information that could be used to describe Guernsey aquifer characteristics (**Plate 3**), even though there was some potential that these wells were completed in or springs discharged from the Fremont Canyon Sandstone or Englewood Formation. Rapp et al. (1957, unnumbered table, p. 23) reported that Guernsey Formation "groundwater possibilities were not known," and Morris and Babcock (1960, Table 1, p. 22) reported that the unit was "generally deeply buried and groundwater possibilities unknown." Because little information is available, classification of the lithostratigraphic unit as a hydrogeologic unit is presumptive, but speculative classification of the Guernsey Formation as an aquifer by previous investigators (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982; WWC Engineering et al., 2007) was retained herein (**Plate K**). These investigators consider the Guernsey Formation to be permeable and classified as an aquifer in areas where structural deformation has resulted in fracturing. Most of these studies (Eisen et al., 1980; Libra et al., 1981; Western Water Consultants, Inc., 1982) also considered the Guernsey aquifer to be part of the Paleozoic aquifer system where hydraulically connected to underlying and overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation; that interpretation also was retained herein (**Plate K**).

7.4.12 Englewood Formation/Limestone

The Early Mississippian Englewood Formation was defined by Sando and Sandberg (1987). Love et al. (1993) referred to the lithostratigraphic unit as the "Englewood Limestone" in their chart summarizing Wyoming Phanerozoic lithostratigraphy, even though the investigators cited Sando and Sandberg (1987) for unit definition. "Englewood Formation" is used in the subsequent description herein. The Englewood Formation consists primarily of poorly resistant "quartz siltstone, very fine- to fine-grained quartz sandstone (quartzarenite), and silty and sandy dolomicrite [finely grained and crystalline micritic dolomite] that weather red, brown, and orange, and platy beds, and thin interbeds and partings of green-weathering silty, sandy clay shale" (Sando and Sandberg, 1987, p. 9). Beds of medium-grained quartz sandstone that in places are conglomeratic and crossbedded also are present in some locations. Formation thickness ranges from about 13 to 45 ft in the northern Laramie Mountains and adjacent areas, including parts of the Hartville Uplift (Sando and Sandberg, 1987). All or parts of the Englewood Formation were assigned to the basal part of the Guernsey Formation in the Glendo and Hartville areas in previous studies (Sando and Sandberg, 1987). No existing information was located describing the physical and chemical hydrogeologic characteristics of the Englewood Formation in the PtRB or elsewhere in Wyoming, so additional description of the lithostratigraphic unit as part of this study was not possible.

7.4.13 Fremont Canyon aquifer

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

Physical characteristics

The Fremont Canyon aquifer consists of saturated and permeable parts of the Late Devonian Fremont Canyon Sandstone (**Plates K, M, U**). The Fremont Canyon Sandstone was defined and described by Sando and Sandberg

(1987), and the brief description of the formation presented herein is from their study. Present in the northern Laramie Mountains and adjacent areas, including parts of the Hartville Uplift, the Fremont Canyon Sandstone ranges from about 6 to 160 ft in thickness where present. Resistant quartzite and cliff-forming friable to indurated quartz sandstone (quartzarenite) composes most of the formation. In the Laramie Mountains, subarkosic quartz sandstone and sandy conglomerate containing granite pebbles are present near the base. Prior to assignment to the newly described Fremont Canyon Sandstone by Sando and Sandberg (1987), these rocks were formerly assigned to the Deadwood Formation and (or) basal Guernsey Formation. In some older and often-cited reports, some of these rocks were considered Cambrian in age and were identified as “quartzite” (for example, Rapp et al., 1957, unnumbered table, p. 23; Morris and Babcock, 1960, Table 1; Welder and Weeks, 1965, Table 1); these rocks are now considered to be part of the Fremont Canyon Sandstone or Englewood Formation.

The Fremont Canyon aquifer is overlain by the Englewood Formation/Limestone in the Hartville Uplift, Laramie Mountains, and Denver-Julesburg Basin (**Plates K, M**), and the Madison aquifer in the Laramie Basin (**Plate U**). The Fremont Canyon aquifer is underlain by the Flathead aquifer or Precambrian basal confining unit (**Plates K, M, U**). Because of potential to be hydraulically connected to overlying Paleozoic hydrogeologic units through extensional fractures in areas of structural deformation (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996), the unit is tentatively assigned to the Paleozoic aquifer system in the Hartville Uplift, Laramie Mountains, and Denver-Julesburg Basin areas (**Plates K, M, U**).

Very little information is available describing the hydrogeology of the Fremont Canyon Sandstone. Hydrogeologic data describing the Fremont Canyon aquifer found in this study were very sparse, but available well-yield and spring-discharge measurements are summarized on **Plate 3**. Assignment of this lithostratigraphic unit to hydrogeologic unit (aquifer or aquifer system) in this study is based on assignment of the unit to the Paleozoic aquifer system along the flanks of the Laramie Mountains and Hartville Uplift in early studies [Eisen et al., 1980; Western Water Consultants, Inc., 1982 (lithostratigraphic unit now known as Fremont Canyon Sandstone is identified as the Deadwood Formation in these studies)] and by observation of physical aquifer characteristics in the Casper Mountain area at the northwestern end of the Laramie Mountains (Stacy, 1994; Stacy and Huntoon, 1994) and the south-central edge of the Powder River Basin near Douglas (Garland, 1996) (**Plates K, M, U**).

Intergranular permeability of sandstones in the aquifer is likely minimal (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). Stacy (1994, p. 41) noted that intergranular permeability of deeply buried subcrops of the Fremont Canyon Sandstone is “locally being destroyed through recrystallization and cementation where groundwaters are supersaturated with respect to various minerals.” Garland (1996) described intergranular permeability in the well-cemented sandstone of the Fremont Canyon Sandstone as “poor.” Joints, bedding-plane partings, and fractures associated with folds and faults likely provide most Fremont Canyon aquifer permeability (Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996). In fact, Garland (1996, p. 20) noted that “up to 25 feet of fair to good permeability in joints and bedding-plane partings was observed in the basal part of the sandstone.” The Fremont Canyon aquifer is likely in hydraulic connection with overlying Paleozoic hydrogeologic units (Casper and Madison aquifers) through extensional fractures in areas of structural deformation, and thus, part of a Paleozoic aquifer system in these areas (Eisen et al., 1980; Western Water Consultants, Inc., 1982; Stacy, 1994; Stacy and Huntoon, 1994; Garland, 1996) (**Plates K, M, U**).

Chemical characteristics

The chemical composition of groundwater in the Fremont Canyon aquifer in the Laramie Mountains (LM) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E5**. Although a TDS concentration was not available, the specific conductance analysis indicated that the water was fresh (**Appendix E5**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Fremont Canyon aquifer in the LM was suitable for most uses. No characteristics or constituents in the Fremont Canyon aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.4.14 Gallatin and Gros Ventre confining units

The Late Cambrian Gallatin Limestone is composed of as much as 450 ft of dense, thinly laminated to massive, glauconitic and oolitic limestone, shale, silty shale, and thin sandstone interbeds (Richter, 1981b, Table IV-1, and references therein). The Middle and Late Cambrian Gros Ventre Formation is composed of as much as 750 ft of limestone, shale, and calcareous shale, with a pebble conglomerate at the base (Richter, 1981b, Table IV-1, and references therein). Both units only are present at land surface and in the subsurface in a small part of the PtRB in the Granite Mountains and southern Wind River Mountains. Both units are relatively impermeable in these areas, so they were classified as confining units by Richter (1981b) and that classification is retained herein (**Plate J**). Where present, both hydrogeologic units confine the underlying Flathead aquifer (**Plate J**). Although classified as regional confining units, parts of the hydrogeologic units may be permeable in areas where joints and fractures are present (Richter, 1981b). Springs discharge small quantities (less than 5 gal/min) of water from the Gallatin confining unit along the Wind River Mountains (Richter, 1981b). No additional information was located describing the physical and chemical hydrogeologic characteristics of the Gallatin and Gros Ventre confining units in the PtRB, so additional description as part of this study was not possible.

7.4.15 Aquifers in undifferentiated Cambrian rocks

The physical and chemical characteristics of aquifers in undifferentiated Cambrian rocks in the PtRB are described in this section of the report.

Physical characteristics

Undifferentiated Cambrian rocks occur in parts of the PtRB, primarily in areas near the Rawlins Uplift, Great Divide Basin, and Granite Mountains. The rocks are described as an upper sequence of red to reddish-brown shale and green glauconitic sandstone, and a lower sequence of medium-grained quartzitic sandstone that is in part cemented by silica and in part conglomeratic (Berry, 1960; Welder and McGreevy, 1966). The upper part seems to correspond to the sandy facies of the Gros Ventre Formation, whereas the lower part seems to correspond to the Flathead Sandstone as reported by Keefer and Van Lieu (1966). The lower sands are a shore and near-shore deposit in front of a transgressive sea, and the upper unit is a shallow marine and non-marine unit (Keefer and Van Lieu, 1966). Berry (1960) reported a thickness range from 0 to 600 ft in the Rawlins Uplift area, but some or all of these rocks are now assigned to the Flathead Sandstone.

Early investigators (Berry, 1960; Welder and McGreevy, 1966; Lowry et al., 1973) had little information available to describe the hydrogeology of undifferentiated Cambrian rocks. Collentine et al. (1981) defined the undifferentiated Cambrian rocks as a “major aquifer” and “major water-bearing zone” in the Great Divide and Washakie Basins. In addition, the investigator combined the rocks with the overlying Madison and Tensleep aquifers into a regional aquifer system defined as the “Paleozoic aquifer system.” The USGS also defined the Cambrian rocks as a “principal aquifer” (Whitehead, 1996) and referred to the rocks as part of the “Paleozoic aquifers” category on the national principal aquifers map (U.S. Geological Survey, 2013).

Few wells are completed in aquifers in undifferentiated Cambrian rocks. Berry (1960, p. 14) reported that sandstones and conglomerates in undifferentiated Cambrian rocks in the Rawlins Uplift area “yield moderate supplies of water to wells.” Hydrogeologic data describing aquifers in undifferentiated Cambrian rocks found in this study were very limited, but available well-yield and spring-discharge measurements are summarized on **Plate 3**.

Chemical characteristics

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

Sweetwater Arch

The chemical composition of aquifers in undifferentiated Cambrian rocks in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (200 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from aquifers in undifferentiated Cambrian rocks in the SA was suitable for most uses. No characteristics or constituents in aquifers in undifferentiated Cambrian rocks approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming basins (south)

The chemical composition of groundwater in aquifers in undifferentiated Cambrian rocks in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (6,680 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the aquifers and undifferentiated Cambrian rocks in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). TDS exceeded State of Wyoming livestock standards (WDEQ Class III standard of 5,000 mg/L).

7.4.16 Flathead aquifer

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

Physical characteristics

The Flathead aquifer consists of the Cambrian Flathead Sandstone, a lithostratigraphic unit present throughout much of the PtRB (**Plates 1 and 2**). The Flathead Sandstone consists of pink, reddish-brown, tan and gray, fine-to medium-grained, arkosic and quartzitic sandstone, with some conglomerate and arkose in the lower part (Keefer and Van Lieu, 1966; Libra et al., 1981, Table IV-1, and references therein; Richter, 1981b, Table IV-1, and references therein). Flathead aquifer thickness varies considerably but generally ranges from 50 to 500 ft (Keefer and Van Lieu, 1966; Richter, 1981b, Table IV-1, and references therein). Depending on location in the PtRB, the Flathead aquifer is overlain by the Gallatin and Gros Ventre confining units in the Granite Mountains and Shirley Basin (**Plate J**); Fremont Canyon aquifer in the Hartville Uplift and the Laramie Mountains (**Plate K**); and the Madison aquifer in the Rawlins Uplift (**Plate S**). The Flathead aquifer is underlain delete by nonporous igneous and metamorphic rocks of the Precambrian basement that comprise a basal confining unit to all aquifers and aquifer systems in the PtRB (**Plates J, K, S**).

Reported descriptions of Flathead aquifer permeability varies by investigator and the location examined. In the Wind River Basin (WRB) and Granite Mountains area, Richter (1981b, Table IV-1) reported that porosity and permeability is intergranular, but that secondary permeability is present along partings between bedding planes and as fractures associated with folds and faults; the investigator classified the Flathead Sandstone as a "major aquifer" in the WRB and adjacent Granite Mountains area (**Plate J**). Boner et al. (1976) and Weston Engineering (2008) noted that the Flathead Sandstone in the southern Powder River Basin and northern flank of the Laramie Mountains was well cemented and poorly sorted with little primary permeability. In addition, Weston Engineering (2008, p. II-4) also noted that bedding-plane partings may provide some permeability, silica cement in the formation is not readily dissolved, and that "permeability of the unit is likely to be similar to that of the underlying Precambrian rocks."

Although considered a potentially good source of groundwater for development by some investigators, the aquifer is essentially undeveloped as a source of groundwater because of deep burial throughout most of the PtRB and the availability of groundwater from shallower aquifers. Water in the aquifer is semiconfined to confined and is likely under high artesian pressures in many areas (Richter, 1981b). Recharge to the Flathead aquifer is likely from infiltration of precipitation and streamflow on outcrop areas, and possibly upward movement of water from the underlying Precambrian basal confining unit (Richter, 1981b). Springs discharge from bedding-plane partings in the unit (Whitcomb and Lowry, 1968; Richter, 1981b). Little hydrogeologic information is available describing the Flathead aquifer because relatively few wells are completed in the unit in the PtRB, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate 3**.

Chemical characteristics

Groundwater-quality data are presented and described for the Flathead aquifer in the PtRB. Groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-2),** and groundwater-quality sample summary statistics tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**).

Sweetwater Arch

The chemical composition of groundwater in the Flathead aquifer in the SA was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (99 mg/L) indicated that the water was fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Flathead aquifer in the SA was suitable for most uses. No characteristics or constituents in the Flathead aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Central Wyoming Basins (south)

The chemical composition of groundwater in the Flathead aquifer in the CBS was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (3,930 mg/L) indicated that the water was moderately saline (TDS concentrations ranging from 3,000 to 9,999 mg/L). Concentrations of some characteristics and constituents in water from the Flathead aquifer in the CBS approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. There were no produced-water constituent analyses that could be compared with health-based standards, but TDS, chloride, and sulfate exceeded aesthetic standards for domestic use (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) and State of Wyoming agricultural-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). No characteristics or constituents exceeded State of Wyoming livestock standards.

7.5 Precambrian basal confining unit

The physical and chemical characteristics of the Precambrian basal confining unit in the PtRB are described in this section of the report.

Physical characteristics

Undifferentiated igneous and metamorphic rocks (including metasedimentary and metavolcanic rocks) of the Precambrian basement act as a basal confining unit for the Flathead aquifer, as well as for all aquifers and aquifer systems in the PtRB (**Plates J, K, M, S, T, U**). Rocks of Precambrian age occur throughout the PtRB and are exposed at land surface as the core rocks of the largest of the uplifts (**Plates 1, 2**). Little is known about Precambrian rocks at depth in the PtRB; however, wells are completed locally for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out—permeability is attributable to weathered, jointed, fractured, or faulted rocks (Berry, 1960; Whitcomb and Lowry, 1968; Lowry et al., 1973; Collentine et al., 1981; Richter, 1981a, b). These investigators also noted that fractures decreased in both size and number at greater depths. Lowry et al. (1973) noted that the shallow permeable zone typically is less than 100-ft deep. Hydrogeologic data describing the Precambrian basal confining unit, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate 3**.

Chemical characteristics

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

Sweetwater Arch

The chemical composition of groundwater in the Precambrian basal confining unit in the Sweetwater Arch (SA) was characterized and the quality evaluated on the basis of environmental water samples from as many as one well and 19 springs. Summary statistics calculated for available constituents are listed in **Appendix E1**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, **diagram C**). TDS concentrations were variable and indicated that all waters were fresh (TDS concentrations less than or equal to 999 mg/L) (**Appendix E1**; **Appendix G1**, **diagram C**; supplementary data tables). TDS concentrations ranged from 34 to 714 mg/L, with a median of 140 mg/L.

Concentrations of some characteristics and constituents in water from the Precambrian basal confining unit in the SA approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards: gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the USEPA MCL of 15 pCi/L) and radon (in both samples analyzed for this constituent, the concentrations exceeded proposed MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L). Concentrations of one characteristic exceeded aesthetic standards for domestic use: TDS (8 percent; USEPA SMCL of 500 mg/L).

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the SA. Constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the WDEQ Class II standard of 15 pCi/L), chloride (8 percent of samples analyzed for the constituent; SMCL of 100 mg/L) and sulfate (8 percent; SMCL of 200 mg/L). One constituent exceeded State of Wyoming livestock standards: gross alpha radioactivity (the concentration in the one sample analyzed for this constituent exceeded the WDEQ Class III standard of 15 pCi/L).

Central Wyoming basins (south)

The chemical composition of groundwater in the Precambrian basal confining unit in the central Wyoming basins (south) (CBS) was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E2**. The TDS concentration (181 mg/L) indicated that the water was fresh (**Appendix E2**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Precambrian basal confining unit in the CBS was suitable for most uses. No characteristics or constituents in the Precambrian basal confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Sierra Madre

The chemical composition of groundwater in the Precambrian basal confining unit in the Sierra Madre (SM) was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (186 mg/L) indicated that the water was fresh (**Appendix E3**; supplementary data tables). On the basis of the characteristics and constituents analyzed, the quality of water from the Precambrian basal confining unit in the SM was suitable for most uses. Three constituents exceeded health-based standards: arsenic (MCL of 10 μg/L), gross alpha radioactivity, and radon (exceeded proposed and alternative MCL). One constituent (gross alpha radioactivity) exceeded State of Wyoming agriculture- and livestock-use standards.

Medicine Bow Mountains

The chemical composition of groundwater in the Precambrian basal confining unit in the Medicine Bow Mountains (MBM) was characterized and the quality evaluated on the basis of environmental water samples from as many as four wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E4**. TDS concentrations were variable and indicated that all waters were fresh (**Appendix E4**; supplementary data tables). TDS concentrations ranged from 55 to 111 mg/L, with a median of 96 mg/L.

Concentrations of few characteristics or constituents in the Precambrian basal confining unit in the MBM approached or exceeded applicable USEPA or State of Wyoming water-quality standards that could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards. Concentrations of one characteristic exceeded aesthetic standards for domestic use and State of Wyoming livestock-use standards: pH (33 percent below lower SMCL and WDEQ Class III limit of 6.5). No characteristics or constituents exceeded State of Wyoming agricultural standards.

Laramie Mountains

The chemical composition of groundwater in the Precambrian basal confining unit in the LM was characterized and the quality evaluated on the basis of environmental water samples from as many as seven wells and eight springs. Summary statistics calculated for available constituents are listed in **Appendix E5**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, **diagram F**). TDS concentrations were variable and indicated that all waters were fresh (**Appendix E5**; **Appendix G3**, **diagram F**; supplementary data tables). TDS concentrations ranged from 45 to 282 mg/L, with a median of 159 mg/L.

Concentrations of few characteristics or constituents in the Precambrian basal confining unit in the LM approached or exceeded applicable USEPA or State of Wyoming water-quality standards that could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent in the one sample analyzed for that constituent exceeded health-based standards: radon (exceeded proposed and alternative MCL). Concentrations of one characteristic exceeded aesthetic standards for domestic use and State of Wyoming livestock-use standards: pH (15 percent below lower limit). No characteristics or constituents exceeded State of Wyoming agricultural standards.