Chapter 7

WBRB Hydrogeologic Units – Physical and Chemical Characteristics

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For this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are summarized in tabular format **(Plate IX)**. The original sources of the data used to construct the summary are listed at the bottom of the plate. Physical characteristics are summarized to provide a broad summary of hydrogeologic-unit characteristics and include spring discharge, well yields, specific capacity, transmissivity, porosity, hydraulic conductivity, and storage (storativity/storage coefficient). Individual data values and corresponding interpretation were utilized and summarized as presented in the original reports – no reinterpretation of existing hydraulic data was made for this study. For example, values of transmissivity derived from aquifer tests were used as published in the original reports, and no reanalysis of previously published aquifer tests was conducted.

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

7.1 Wind River Basin

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

7.1.1 Quaternary unconsolidated-deposit aquifers

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

Physical characteristics

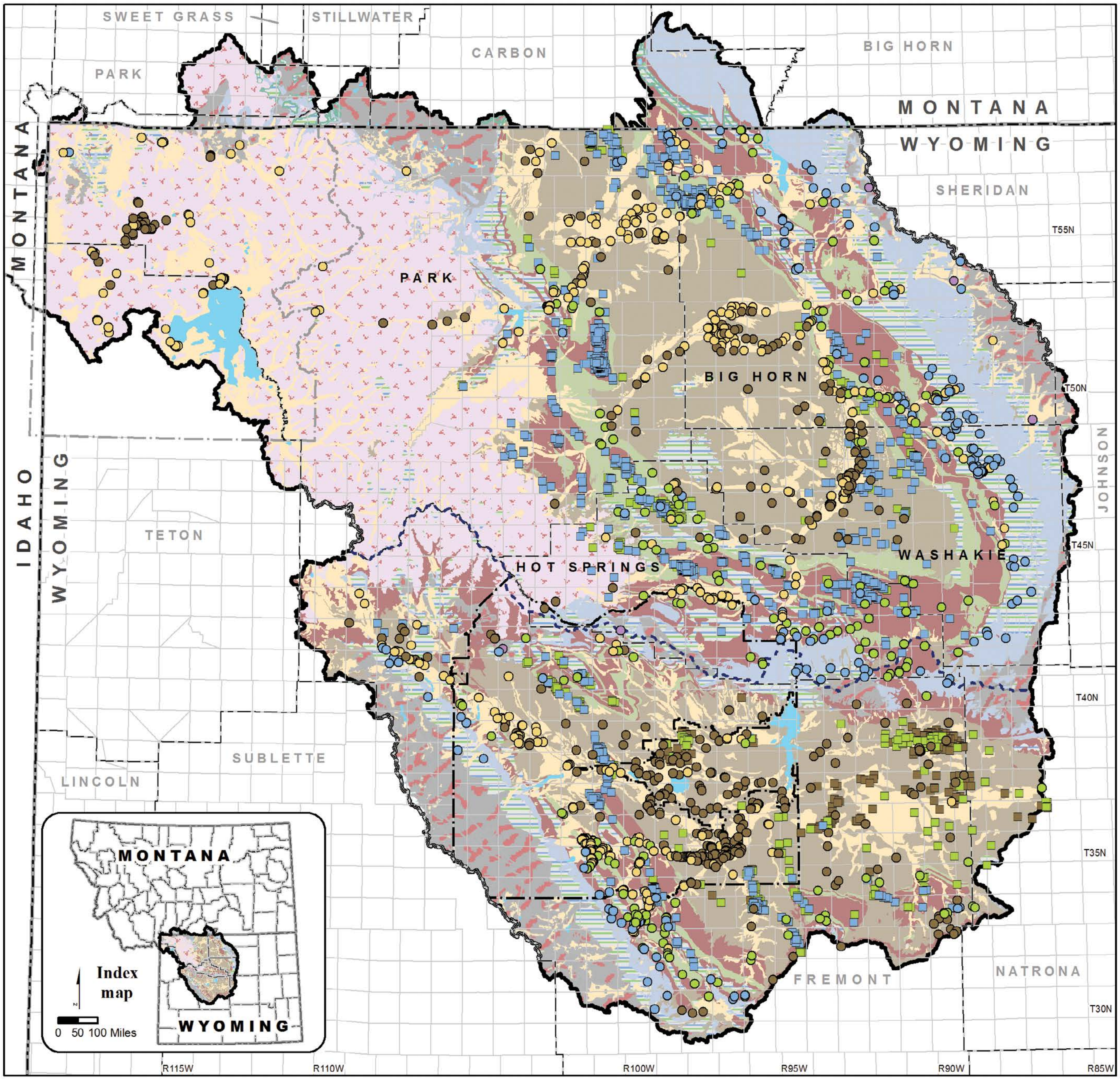
Unconsolidated deposits of Quaternary age contain aquifers (referred to herein as "Quaternary unconsolidated-deposit aquifers") that can be highly productive locally and are the source of water for many shallow wells in the WRB. In the WRB, Quaternary unconsolidated-deposit aquifers are used as sources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

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

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

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

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



Explanation

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

Environmental groundwater sample location

- Quaternary
- Cenozoic
- Mesozoic
- Paleozoic
- Precambrian

Produced groundwater sample location

- Cenozoic
- Mesozoic
- Paleozoic

Hydrologic divide between the Wind and Bighorn river basins

Yellowstone National Park boundary

Wind River Indian Reservation boundary

Hydrogeologic unit

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

0 5 10 20 30 Miles

N

WSGS 2011

Projection: NAD 1983
UTM Zone 12N

Data Source:

U.S. Geological Survey

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

Recharge, discharge, and groundwater movement

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

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

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

Chemical characteristics

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

Alluvial aquifers

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

Concentrations of some properties and constituents in water from alluvial aquifers in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent exceeded the proposed MCL, whereas 20 percent exceeded the alternative MCL), boron (2 percent), nitrate plus nitrite (2 percent), and nitrate (2 percent).

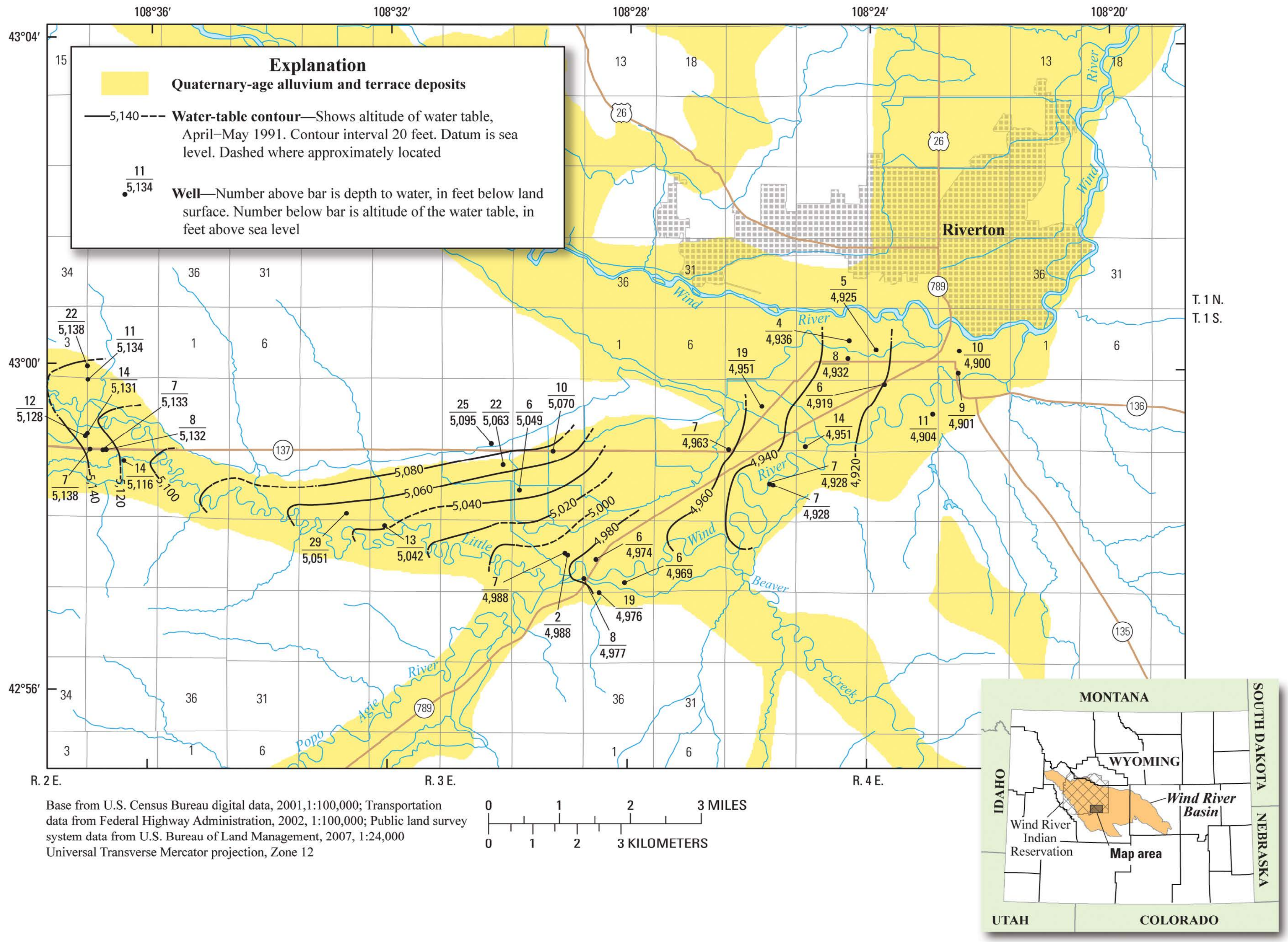


Figure 7-2. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the lower Little Wind River Basin, Wyoming (modified from Daddow, 1996, Plate II).

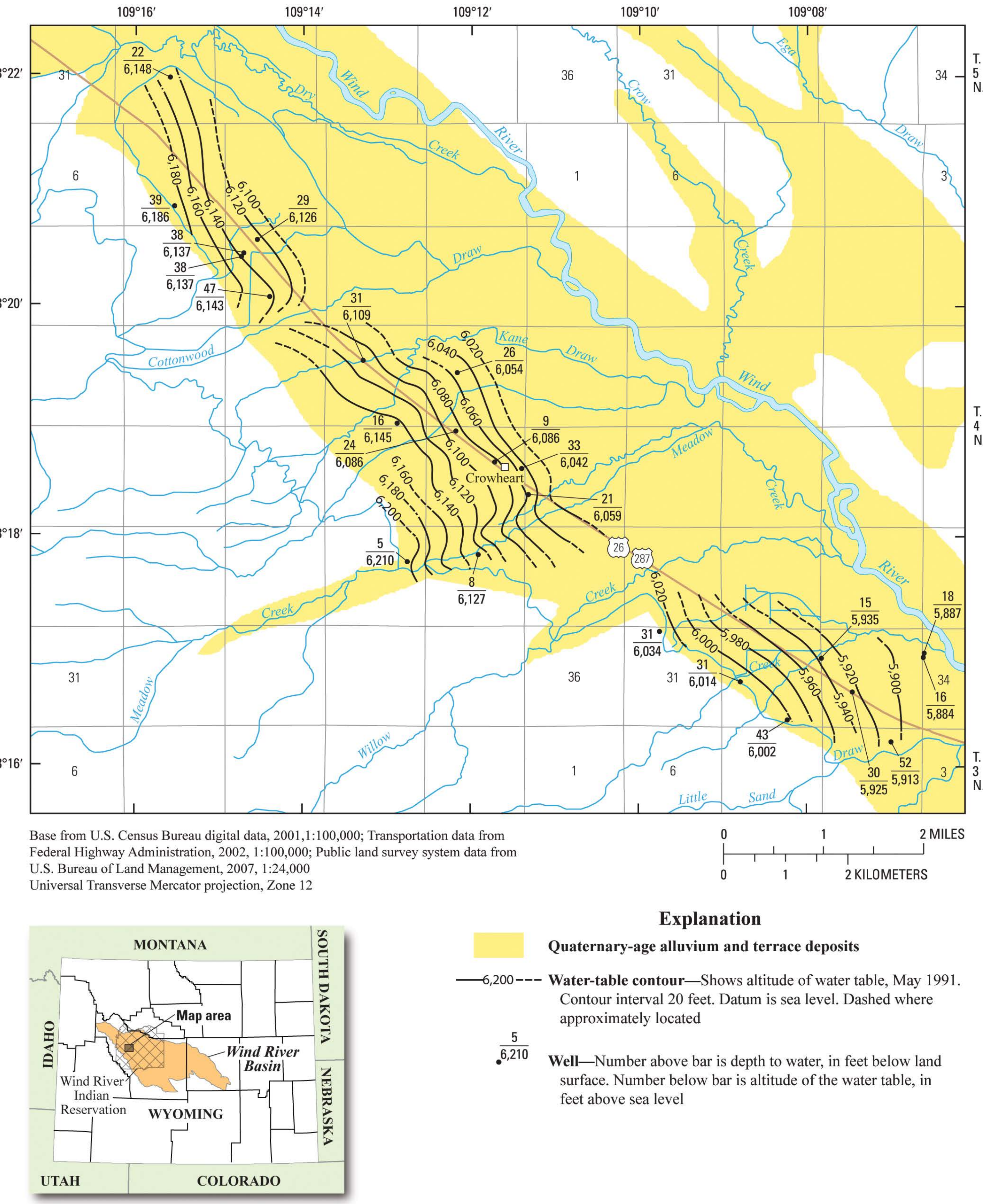


Figure 7-3. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the Crowheart area of the Wind River Indian Reservation, Wyoming (modified from Daddow, 1996, Plate III).

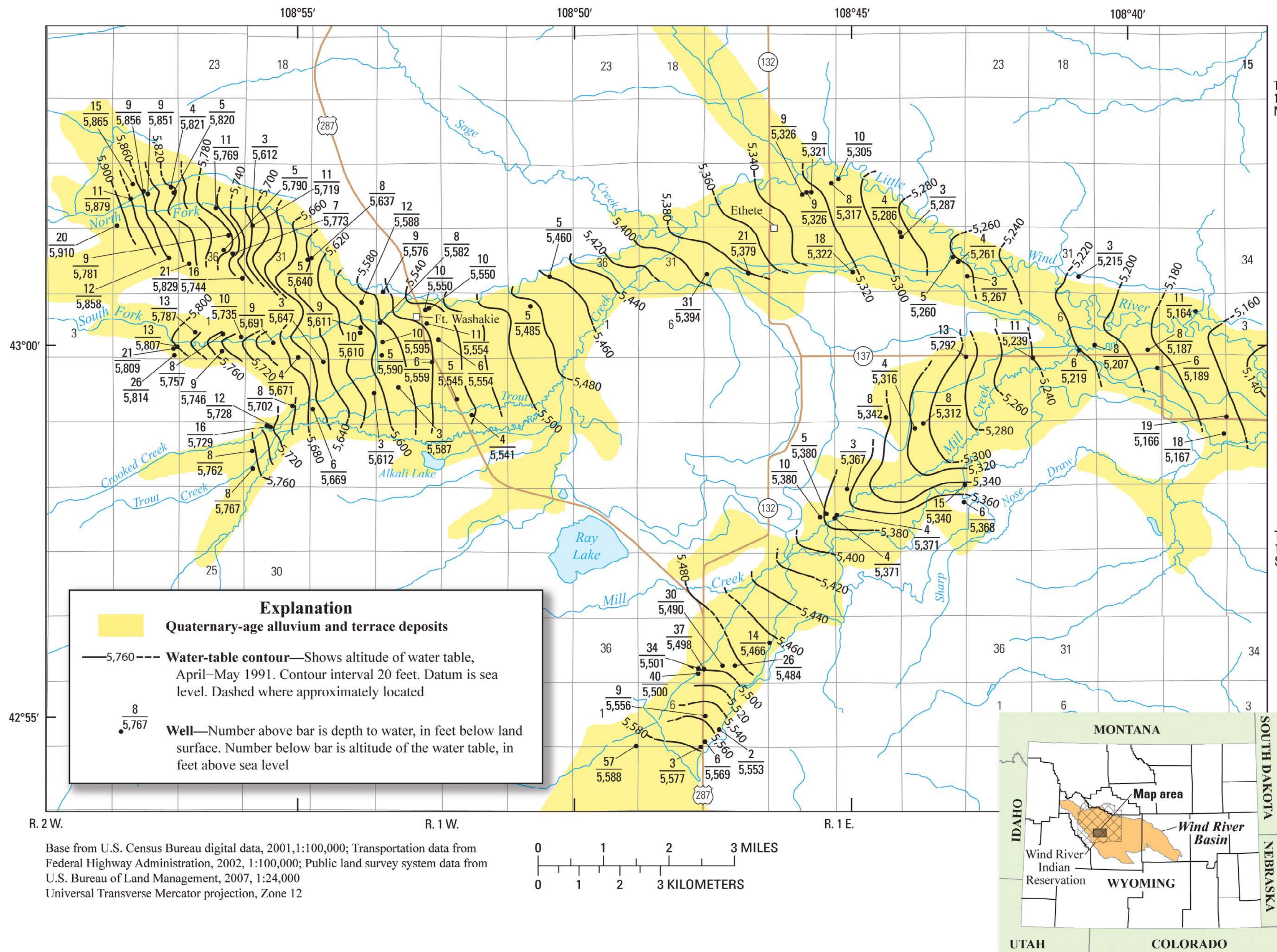


Figure 7-4. Water-table contours and depth to water in Quaternary unconsolidated-deposit aquifers in the upper Little Wind River and Mill Creek Basins, Wyoming (modified from Daddow, 1996, Plate II).

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

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

Terrace-deposit aquifers

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

Concentrations of some properties and constituents in water from terrace-deposit aquifers in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent) and fluoride (7 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (69 percent), sulfate (44 percent), manganese (17 percent), filtered iron (10 percent), fluoride (7 percent), and pH (6 percent below lower limit and 6 percent above upper limit).

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

Aquifers in landslide deposits

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

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

Aquifers in dune sand (eolian) deposits

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

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

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

Glacial-deposit aquifers

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

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

7.1.2 Split Rock aquifer

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

7.1.3 White River aquifer

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

Physical characteristics

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

Chemical characteristics

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

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

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

7.1.4 Aycross–Wagon Bed confining unit

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

Physical characteristics

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

Chemical characteristics

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

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

7.1.5 Wind River aquifer

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

Physical characteristics

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

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

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

McGreevy et al. (1969) qualitatively divided the Wind River Formation on the Wind River Indian Reservation into three distinct sequences (facies) – (1) a several-thousand-foot-thick lower fine-grained sequence composed of brown, maroon, red, and gray siltstone and shale with predominantly fine-grained sandstone; (2) an approximately 1,000-ft thick middle coarse-grained sequence composed of green and gray, coarse-grained arkosic sandstone, conglomerate, and siltstone; and (3) an upper facies (present in the eastern part of the reservation) as much as 800 ft thick composed of gray and green siltstone, shale, and fine-grained sandstone with thin beds of red, maroon, and green siltstone and shale. McGreevy et al. (1969, p. I44) noted that the middle coarse-grained sequence intertongues with and underlies the upper fine-grained sequence, and that "many of the coarse-grained sandstone and conglomerate beds are very well sorted, loosely cemented, and very porous."

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

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

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

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

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

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

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

Chemical characteristics

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

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

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

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

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

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

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

7.1.6 Indian Meadows confining unit

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

7.1.7 Fort Union–Lance aquifer

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

Physical characteristics

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

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

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

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

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

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

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

Concentrations of some properties and constituents in environmental water samples from the Fort Union aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): ammonia (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (100 percent), filtered iron (100 percent), fluoride (50 percent), pH (33 percent above upper limit), and sulfate (33 percent).

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

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

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

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

Concentrations of some properties and constituents in water from the Lance aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of one constituent that always exceeded health-based standards (USEPA MCLs and HALs): barium (100 percent of samples analyzed for the constituent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), chloride (98 percent), filtered iron (96 percent), sulfate (25 percent), and pH (5 percent below lower limit and 14 percent above upper limit). TDS concentrations in 21 percent of produced-water samples from the Lance aquifer exceeded State of Wyoming Class IV standards.

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

7.1.8 Meeteetse–Lewis confining unit

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

Physical characteristics

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

Chemical characteristics

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

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

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

7.1.9 Mesaverde aquifer

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

Physical characteristics

The Upper Cretaceous-age Mesaverde Formation comprises the Mesaverde aquifer in the WRB **(Plate II)**. The Mesaverde Formation consists of a variable sequence of massive lenticular fine- to coarse-grained sandstone, carbonaceous shale, and lesser amounts of coal (Johnson et al., 2007, and references therein). Reported thickness of the Mesaverde Formation (including all members) ranges from 500 ft in the eastern WRB to 2,200 ft in the western WRB (Johnson et al., 2007, fig. 9). As many as four members of the Mesaverde Formation are recognized in the eastern WRB – the uppermost Teapot Sandstone Member, the middle unnamed member, the Parkman Sandstone Member, and the lowermost Fales Sandstone Member **(Plate II)** (Johnson et al., 2007, and references therein). The Wallace Creek Tongue of the Cody Shale separates the Parkman and Fales Sandstone Members **(Plate II)**. In the southern, central, and western WRB, the Mesaverde Formation is subdivided into the Teapot Sandstone Member and an underlying informally named "lower part" (not shown on Plate II; see Johnson et al., 2007, Figure 2). As their names imply, the Teapot Sandstone, Parkman Sandstone, and Fales Sandstone Members are composed primarily of sandstone, and these members are defined as aquifers or subaquifers (Richter, 1981; **Plate II**). The unnamed middle member is composed of siltstone, shale, carbonaceous shale, and thin-bedded, discontinuous sandstone; this member and the intertonguing Wallace Creek Tongue of the Cody Shale are defined as confining units (Richter, 1981; **Plate II**). Both these confining units, along with the regionally extensive Meeteetse-Lewis and Cody confining units, create the series of confined sandstone subaquifers (Teapot Sandstone, Parkman Sandstone, and Fales Sandstone aquifers) composing the Mesaverde aquifer **(Plate II)**. In some parts of the WRB, the sandstone subaquifers may be hydraulically connected by faults and fractures in underlying and overlying confining units (Richter, 1981).

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

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

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

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

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

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

Chemical characteristics

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

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

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

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

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

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

7.1.10 Cody confining unit

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

Physical characteristics

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

Chemical characteristics

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

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

Concentrations of some properties and constituents in water from the Cody confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): nitrate (50 percent of samples analyzed for the constituent), ammonia (33 percent), selenium (33 percent), and nitrate plus nitrite (20 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (91 percent), sulfate (91 percent), manganese (67 percent), filtered iron (50 percent), pH (20 percent above upper limit), and fluoride (9 percent).
Chemical analyses of many properties and constituents were not available for the produced-water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA MCLs and HALs) for domestic use: TDS (98 percent), iron

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

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

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

7.1.11 Lower and middle Mesozoic aquifers and confining units

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

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

7.1.11.1 Frontier aquifer

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

Physical characteristics

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

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

Chemical characteristics

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

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

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

Concentrations of some properties and constituents in the Frontier aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): boron (40 percent of samples analyzed for the constituent) and nitrate (17 percent). Concentrations of several properties and constituents exceeded aesthetic standards for domestic use: TDS (68 percent), sulfate (53 percent), manganese (25 percent), filtered iron (17 percent), chloride (11 percent), pH (6 percent above upper limit), and fluoride (6 percent).

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

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

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

7.1.11.2 Mowry–Thermopolis confining unit

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

Physical characteristics

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

With the exception of oil and gas wells, very few wells are installed in the Mowry–Thermopolis confining unit; development is likely limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Most information describing the formations is from oil and gas well data. Hydrogeologic information available describing the Mowry–Thermopolis confining unit, including well-yield and spring-discharge measurements and other hydraulic properties for all three lithostratigraphic units composing the hydrogeologic unit, are summarized on **Plate IX**.

Chemical characteristics

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

7.1.11.2.1 Mowry confining unit

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

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

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

7.1.11.2.2 Muddy Sandstone aquifer

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

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

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

7.1.11.2.3 Thermopolis confining unit

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

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

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

7.1.11.3 Cloverly aquifer

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

Physical characteristics

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

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

Chemical characteristics

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

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

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

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

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

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

7.1.11.4 Morrison confining unit

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

Physical characteristics

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

Chemical characteristics

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

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

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

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

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

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

7.1.11.5 Sundance–Nugget aquifer

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

Physical characteristics

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

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

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

Chemical characteristics

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

7.1.11.5.1 Sundance aquifer

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

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

For the produced-water samples, few analyses of properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), chloride (88 percent), sulfate (88 percent), and pH (25 percent below lower limit). TDS concentrations in 62 percent of produced-water samples from the Sundance aquifer exceeded State of Wyoming Class IV standards.

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

7.1.11.5.2 Gypsum Spring confining unit

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

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

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

7.1.11.5.3 Nugget aquifer

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

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

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

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

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

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

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

7.1.11.6 Chugwater–Dinwoody aquifer and confining unit

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

Physical characteristics

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

Chemical characteristics

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

7.1.11.6.1 Chugwater aquifer

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

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

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

Most available water-quality analyses for the Chugwater aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards for domestic use: TDS (100 percent), sulfate (80 percent), filtered iron (67 percent), chloride (64 percent), and pH (1 percent below lower limit and 10 percent above upper limit). TDS concentrations in 27 percent of produced-water samples from the Chugwater aquifer exceeded State of Wyoming Class IV standards.

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

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

7.1.11.6.2 Dinwoody confining unit

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

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

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

7.1.11.7 Recharge, discharge, and groundwater movement

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

Discharge is both natural and anthropogenic. Groundwater naturally discharges from the lower and middle Mesozoic aquifers and confining units through seeps, springs, interformational movement, and gaining streams (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). Some discharge from springs results from erosional downcutting of aquifers by streams (McGreevy et al., 1969). Richter (1981, p. 76) noted numerous springs (generally discharging less than 25 gal/min), many of which are controlled by faults and fractures, discharging from the Frontier aquifer along the Wind River Range. The primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are oil and gas wells.

No potentiometric-surface maps have been constructed for any of the hydrogeologic units included in the lower and middle Mesozoic aquifers and confining units; however, Richter (1981, p. 91-93) examined generalized regional groundwater movement in the "Lower Cretaceous rocks" of the WRB. Using potentiometric indicators such as static water levels, altitudes of springs, and petroleum drill-stem tests, he concluded that water movement in these units is generally basinward (Richter, 1981, Figure 5-1).

7.1.12 Goose Egg–Phosphoria aquifer and confining unit

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

Physical characteristics

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

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

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

Chemical characteristics

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

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

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

Concentrations of some properties and constituents in the Phosphoria aquifer and confining unit in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of gross alpha radioactivity and radium-226 plus radium-228 exceeded health-based standards (USEPA MCL) in one sample. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (62 percent of samples analyzed for the property), sulfate (54 percent), and fluoride (8 percent).

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

Concentrations of some properties and constituents in water from the Phosphoria aquifer and confining unit exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent), radium-226 plus radium-228 (100 percent), sulfate (54 percent), TDS (15 percent), and chloride (8 percent). Concentrations of one property and one constituent exceeded State of Wyoming livestock standards in one sample: gross alpha radioactivity and radium-226 plus radium-228.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (85 percent), chloride (78 percent), and sulfate (95 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (54 percent), sulfate (33 percent), chloride (28 percent), and pH (4 percent below lower limit and 8 percent above upper limit).

7.1.13 Paleozoic aquifer system

The Paleozoic aquifer system in the WRB is contained within lithostratigraphic units ranging in age from Middle Ordovician to Pennsylvanian **(Plate II)**. The Paleozoic aquifer system in the WRB defined herein is composed of five hydrogeologic units – the Tensleep aquifer, Amsden aquifer, Madison aquifer, Darby aquifer, and Bighorn aquifer **(Plate II)**. The Paleozoic aquifer system is confined above by overlying low-permeability shales and siltstones of the Goose Egg–Phosphoria aquifer and confining unit and confined below by thick, low-permeability shales of the Gallatin–Gros Ventre confining unit **(Plate II)**. The Paleozoic aquifer system is about 2,000 ft thick, and underlies the entire WRB except the Granite Mountains area (Richter, 1981). Formations composing the aquifer system crop out along the margins of the Wind River Range, Owl Creek Mountains, and Rattlesnake Hills **(Plate I)**.

The Paleozoic aquifer system includes some of the most important aquifers in the WRB. Depending on location and depth, wells completed in the aquifers produce highly variable quantities and qualities of water. Except near outcrops, where water-table (unconfined) conditions may occur, groundwater in the Paleozoic aquifer system generally is semi-confined or confined. With the exception of wells utilized for oil and gas production, most wells completed in the Paleozoic aquifer system in the WRB are located in or near outcrops along basin margins or along basin margins where drilling depths are shallow and economical.

Permeability in the Paleozoic aquifer system aquifers is controlled by lithology, sedimentary structure and depositional environment, and tectonic structure (Richter, 1981). The predominant lithologies of the lithostratigraphic units composing the aquifer system are sandstone, carbonates (limestone and dolomite), and shale. Primary porosity and intergranular permeability are much greater in the sandstones than in the carbonates and shale, where primary permeability is very low (Richter, 1981). Carbonate aquifers generally are only utilized in areas where substantial secondary permeability is developed, most commonly in areas of structural deformation (for example, anticlines) and its associated faults and fractures.

The Tensleep and Madison aquifers are the most productive (permeable) aquifers in the Paleozoic aquifer system; consequently, both aquifers are utilized substantially more than the Amsden, Darby, and Bighorn aquifers (Richter, 1981). In fact, relatively few wells are completed in the Amsden, Darby, and Bighorn aquifers because of their lower primary permeability. The Tensleep and Madison aquifers are considered "major" or "principal" aquifers because wells at some locations yield hundreds of gallons per minute. Thus, the aquifers can be developed for domestic, public supply, or stock use at some locations in the WRB, where groundwater quality is acceptable for these uses. Both aquifers also are extensively utilized for oil and gas production in the basin.

The groundwater quality of aquifers in the Paleozoic aquifer system varies greatly throughout the WRB. Recharge to the aquifer system generally occurs where the formations crop out near basin margins. Near recharge areas, water in the aquifer system may be relatively fresh and suitable for most uses. This is where most domestic, public-supply, or stock wells are completed. Elsewhere, and with increasing depth (as indicated primarily by produced-water samples) and as the water moves away from outcrops into the basin interior, the water may have large TDS concentrations (be highly mineralized) and be unsuitable for most uses or only marginally suitable for livestock and other uses. Only oil or gas wells are completed in deeply buried Paleozoic stratigraphic units.

7.1.13.1 Tensleep aquifer

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

Physical characteristics

The Tensleep aquifer is a major aquifer in the WRB. The Middle and Upper Pennsylvanian-age Tensleep Sandstone comprises the Tensleep aquifer in the WRB **(Plate II)**. The Tensleep aquifer is composed of predominantly tan, massive to cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica (Todd, 1963; Keefer and Van Lieu, 1966; Richter, 1981; Love et al., 1993). Irregular chert layers and thin limestones and dolomites also are present (Richter, 1981). Reported thickness of the hydrogeologic unit in the WRB ranges from 200 to 600 ft (Richter, 1981, table IV-1). The Tensleep aquifer is the uppermost hydrogeologic unit of the Paleozoic aquifer system. The Tensleep Sandstone is overlain by the Phosphoria or Goose Egg Formations and underlain by the Amsden Formation **(Plate II)**. No regional confining unit separates the Tensleep aquifer from the underlying Amsden aquifer.

The Tensleep aquifer is used primarily as a source of water for domestic, public-supply, industrial, and (rarely) irrigation purposes (Plafcan et al., 1995). The Tensleep aquifer is productive throughout the WRB; and, on the basis of well yields, the uppermost 200 ft of the aquifer is the most productive (Richter, 1981). Hydrogeologic data describing the Tensleep aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**. Spring and well yields and transmissivities from the Tensleep aquifer compiled for this study **(Plate IX)** indicate that it is one of the most productive hydrogeologic units in the Wind River Basin. In fact, the median spring and well yield (67.5 gal/min) is second only to that of the Madison aquifer among lithostratigraphic units in the WRB **(Plate IX)**. Most wells completed in the Tensleep aquifer are located along the basin margin where the Tensleep Sandstone crops out or is present at shallow depth. Many wells flow at land surface due to artesian pressure. Large volumes of water are withdrawn from the numerous oilfields in the basin.

On the basis of studies conducted in the Bighorn Basin, porosity and permeability in the Tensleep aquifer is thought to be primarily intergranular and to depend on the amount of secondary cementation and re-crystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966). Emmett et al. (1971) noted that highly crossbedded sandstones had lower permeabilities than regular bedded sandstones. Fractures and solution processes (in carbonate-rich zones) may enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976; Richter, 1981). Secondary fracture porosity and permeability is common in folds and faults that deform the Tensleep Sandstone, and these locations, as reported in numerous studies in the Bighorn Basin, have the best potential for groundwater development (Western Water Consultants, Inc., 1982a,b; Jarvis, 1986a; Spencer, 1986a); by inference, the same potential likely exists in the WRB as well. In fact, Whitcomb and Lowry (1968) noted that the most productive wells in the Tensleep aquifer are associated with local structures where fracturing has increased permeability, and Richter (1981) noted that permeability in highly fractured parts of the aquifer along the Wind River Range might be several orders of magnitude greater than permeability in relatively undeformed areas such as the central WRB.

Chemical characteristics

The chemical composition of groundwater in the Tensleep aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from 14 wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G1**, diagram H). TDS concentrations were variable and indicated that most waters were fresh (93 percent of samples) and the remaining waters were slightly saline (**Appendix E1**; **Appendix G1**, diagram H; supplementary data tables). TDS concentrations ranged from 146 to 1,060 mg/L, with a median of 208 mg/L.

The chemical composition of groundwater in the Tensleep aquifer also was characterized and the quality evaluated on the basis of 114 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H1**, diagram L). TDS concentrations from produced-water samples were highly variable, ranging from fresh to very saline (**Appendix F1; Appendix H1**, diagram L; supplementary data tables). TDS concentrations ranged from 167 to 25,600 mg/L, with a median of 2,930 mg/L.

Concentrations of some properties and constituents in the Tensleep aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one property and two constituents commonly exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), gross alpha radioactivity (50 percent), and radium-226 plus radium-228 (33 percent). Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (13 percent) and sulfate (7 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (100 percent), TDS (95 percent), sulfate (94 percent), chloride (40 percent), and pH (2 percent below lower limit and 8 percent above upper limit). TDS concentrations in 11 percent of produced-water samples from the Tensleep aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Tensleep aquifer exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (50 percent), radium-226 plus radium-228 (33 percent), and sulfate (7 percent). Concentrations of one property and one constituent exceeded State of Wyoming livestock standards: gross alpha radioactivity (50 percent) and radium-226 plus radium-228 (33 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (95 percent), TDS (83 percent), and chloride (77 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (19 percent), chloride (9 percent), sulfate (9 percent), and pH (2 percent below lower limit and 8 percent above upper limit).

7.1.13.2 Amsden aquifer

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

Physical characteristics

The permeable parts of the Lower Pennsylvanian- and Upper Mississippian-age Amsden Formation compose the Amsden aquifer in the WRB (**Plate II**; Richter, 1981). The Amsden aquifer is part of the Paleozoic aquifer system. The Amsden Formation is overlain by the Tensleep Sandstone and underlain by the Madison Limestone **(Plate II)**. The Amsden Formation is composed of two stratigraphic sequences—a complex upper sequence of "nonresistant shale, dense dolomite, thin cherty limestone, and thin, resistant, fine-grained sandstone," and the basal Darwin Sandstone Member, composed of a "fine- to medium-grained, cross-bedded to massive, friable, porous sandstone" (Richter, 1981, table IV-1, from Keefer and Van Lieu, 1966). Reported thickness of the Amsden Formation ranges from 0 to 400 ft in the WRB (Richter, 1981, table IV-1). Permeability in the Darwin Sandstone is attributed to joints and partings between bedding planes, whereas permeability of both the upper and basal sequences may be substantially enhanced where fractured (Richter, 1981). Essentially no development of the aquifer has occurred because higher yields can be obtained from wells completed in other aquifers within the Paleozoic aquifer system, commonly at shallower depth. Consequently, almost no study of the aquifer has occurred, and the little quantitative hydrogeologic information that could be located for the Amsden aquifer in the WRB is presented on **Plate IX**.

The water-bearing potential of the Amsden aquifer near Lander was briefly mentioned by Weston Engineering, Inc. (2004a; 2004b, p. IV-1). The investigators noted "tightness" and little water production when attempting to drill through the Amsden Formation to reach the underlying Madison aquifer.

Chemical characteristics

The chemical composition of groundwater in the Amsden aquifer in the WRB was characterized and the quality evaluated on the basis of one produced-water sample. Individual constituent concentrations are listed in **Appendix F1**. The TDS concentration (6,100 mg/L) indicated that the water was moderately saline. Health-based standards (USEPA MCLs and HALs) were not applicable for any of the constituents analyzed for in the produced-water sample. Concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs) for domestic use, as well as standards for agricultural use. Concentrations of TDS and sulfate also exceeded livestock-use standards.

7.1.13.3 Madison aquifer

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

Physical characteristics

The Madison aquifer is a major aquifer in the WRB. The permeable parts of the Lower and Upper Mississippian-age Madison Limestone compose the Madison aquifer in the WRB **(Plate II)**. The Madison Limestone is composed of two stratigraphic members – an upper member, about 100 ft thick, consisting of thin to massive, irregularly bedded, gray to tan limestone and dolomite, and a lower member, about 500 to 600 ft thick, consisting of predominantly bluish-gray to gray, massive to thin-bedded, crystalline limestone and dolomitic limestone (Keefer and Van Lieu, 1966). The Madison Limestone is overlain by the Amsden Formation and underlain by the Darby Formation **(Plate II)**. No regional confining units separate the Madison aquifer from the Amsden and Darby aquifers. The Madison Limestone is locally cavernous in outcrop areas.

Permeability in the Madison aquifer is primarily secondary and is attributed to solution-enhanced fractures, joints, and caverns (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Primary permeability is very low to nonexistent because of the dense and finely crystalline structure of the carbonates composing the aquifer (Richter, 1981). Without development of secondary permeability, well yields in the Madison aquifer are likely to be relatively small (for example, see results of exploratory drilling in Wyoming Water Development Commission, 1996). The most productive (permeable) parts of the Madison aquifer are areas with substantial fractures and cavernous zones (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981; Jorgensen Engineering and Land Surveying, 1995). Richter noted that most cavern development is in the upper one-third of the Madison Limestone.

The Madison aquifer is used as a source of water for domestic, commercial, stock, public supply, industrial, and (rarely) irrigation purposes (Plafcan et al., 1995). The aquifer is highly productive. Hydrogeologic data describing the Madison aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**. Spring and well yields and transmissivities from the Madison aquifer compiled for this study **(Plate IX)** indicate that it is the most productive hydrogeologic unit in the Wind River Basin. In fact, the median spring and well yield (90 gal/min) is the highest calculated for lithostratigraphic units in the WRB **(Plate IX)**. Most wells completed in the Madison aquifer are located along the basin margin where the Madison Limestone crops out or is present at relatively shallow depth. Water in the aquifer is generally confined, and most wells flow at land surface due to artesian pressure. Large volumes of water also are withdrawn from the numerous oil fields in the Wind River Basin.

Chemical characteristics

The chemical composition of groundwater in the Madison aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from nine wells and five springs. Summary statistics calculated for available constituents are listed in **Appendix E1**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix E1; Appendix G1**, diagram I). TDS concentrations indicated that the waters were fresh. TDS concentrations ranged from 181 to 920 mg/L, with a median of 216 mg/L.

The chemical composition of groundwater in the Madison aquifer also was characterized and the quality evaluated on the basis of 64 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F1**. TDS concentrations from produced-water samples were highly variable and ranged from fresh to very saline, but most were slightly saline (70 percent) (**Appendix F1; Appendix H1**, diagram M; supplementary data tables). TDS concentrations ranged from 291 to 30,600 mg/L, with a median of 2,040 mg/L.

Concentrations of some properties and constituents in the Madison aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): arsenic (17 percent of samples analyzed for the constituent) and radium-226 plus radium-228 (17 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (29 percent), TDS (15 percent), filtered iron (14 percent), and sulfate (8 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. In the one produced-water sample analyzed for arsenic, the arsenic concentration exceeded the health-based standard (USEPA MCL). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (98 percent), sulfate (98 percent), chloride (73 percent), filtered iron (25 percent), manganese (20 percent), and pH (3 percent below lower limit and 3 percent above upper limit). TDS concentrations in 8 percent of produced-water samples from the Madison aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Constituents in environmental water samples that had concentrations greater than agricultural-use standards were radium-226 plus radium-228 (17 percent) and sulfate (8 percent). Concentrations of one constituent exceeded State of Wyoming livestock standards: radium-226 plus radium-228 (17 percent).

The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded agricultural-use standards: arsenic (100 percent), sulfate (98 percent), TDS (53 percent), and chloride (92 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: arsenic (100 percent), TDS (16 percent), chloride (14 percent), pH (3 percent below lower limit and 3 percent above upper limit), and sulfate (2 percent).

7.1.13.4 Darby aquifer

The permeable parts of the Upper Devonian-age Darby Formation compose the Darby aquifer in the WRB **(Plate II)**. The Darby Formation, present only in the western WRB, is composed of resistant dolomite, siltstone, and shale (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Reported thickness of the Darby Formation ranges from 0 to 200 ft (Keefer, and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Darby Formation likely functions as an aquifer only in areas with substantial secondary permeability (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Richter (1981, table IV-1, p. 52) noted that the formation could be "generally considered a confining unit, but permeable along joints and fractures." Nonetheless, Richter classified the formation as an aquifer, and that classification has been utilized by subsequent investigators and is retained herein. Joints in the aquifer provide small quantities of water (generally less than 10 gal/min) to numerous springs along the Wind River Range (Richter, 1981, table IV-1, p. 52). The Darby aquifer is part of the Paleozoic aquifer system. The Darby Formation is overlain by the Madison Limestone and underlain by the Bighorn Dolomite **(Plate II)**. No regional confining units separate the Darby aquifer from the Madison and Bighorn aquifers. Essentially no quantitative hydrogeologic information is available describing the physical or chemical characteristics of the Darby aquifer in the WRB because few, if any, wells are completed in the aquifer.

7.1.13.5 Bighorn aquifer

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

Physical characteristics

The permeable parts of the Middle and Upper Ordovician-age Bighorn Dolomite compose the Bighorn aquifer in the WRB **(Plate II)**. The Bighorn Dolomite is composed of two stratigraphic sequences – the upper Leigh Dolomite Member composed of dense, thin-bedded to massive dolomite and the basal Lander Sandstone Member, composed of fine- to medium-grained sandstone (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Reported thickness of the Bighorn Dolomite ranges from 0 to 300 ft (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Permeability in the basal Lander Sandstone Member likely is both primary (intergranular) and secondary (joints and fractures), whereas permeability in the upper Leigh Dolomite Member is secondary (joints and fractures) (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981). Joints in the aquifer provide small quantities of water (generally less than 10 gal/min) to numerous springs along the Wind River Range (Richter, 1981, table IV-1, p. 52 and p. 68). The Bighorn aquifer is the basal hydrogeologic unit of the Paleozoic aquifer system. The Bighorn Dolomite is overlain by the Darby Formation and underlain by the regionally extensive Gallatin Limestone **(Plate II)**. Little quantitative hydrogeologic information is available describing the physical or chemical characteristics of the Bighorn aquifer in the WRB because few wells are completed in the aquifer, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Bighorn aquifer in the WRB was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in Appendix E1. TDS concentrations indicated that waters were fresh. TDS concentrations ranged from 102 to 222 mg/L, with a median of 178 mg/L. On the basis of the few properties and constituents analyzed for in the three spring samples, waters were likely suitable for most uses as no properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.1.13.6 Groundwater recharge, discharge, and movement

Aquifers in the Paleozoic aquifer system are recharged primarily from precipitation (rain and snow melt) and streamflow infiltrating outcrops along mountain-basin margins (Whitcomb and Lowry, 1968; Richter, 1981; Jorgensen Engineering and Land Surveying, 1993a,b). Richter (1981, p. 69) reported that "excellent recharge potential exists along the elevated flanks of the Wind River and Owl Creek Mountains, where annual precipitation exceeds 60 inches per year and numerous perennial streams flow across outcrops." Substantial streamflow losses may occur where streams cross karstic Paleozoic-age rocks. In Sinks Canyon, west of Lander along the flanks of the Wind River Range, the Middle Popo Agie River loses all flow to the karstic Madison Limestone as it flows across the outcrop; flow reappears about one-half mile downstream (Whitcomb and Lowry, 1968).

Discharge from aquifers of the Paleozoic aquifer system is both natural and anthropogenic. Richter (1981) reported small spring flows (generally less than 10 gal/min) from Paleozoic aquifers along the Wind River Range. Other sources of natural discharge from aquifers in the Paleozoic aquifer system include numerous springs, gaining streams, and other aquifers. Some springs discharge thermal waters (Breckenridge and Hinckley, 1978; Hinckley et al., 1982a,b; Hinckley and Heasler, 1987). Large thermal springs from the Madison aquifer and adjacent aquifers in the Paleozoic aquifer system discharge at the mouths of the canyons of Warm Spring Creek and Little Warm Spring Creek near Dubois (Breckenridge and Hinckley, 1978; Hinckley et al., 1982a,b; Hinckley and Heasler, 1987; Jorgensen Engineering and Land Surveying, 1995). The primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are large-capacity public-supply, irrigation, and oil and gas wells (Whitcomb and Lowry, 1968; Richter, 1981; Plafcan et al., 1995; Daddow, 1996). No potentiometric-surface maps have been constructed showing groundwater flow in aquifers of the Paleozoic aquifer system.

7.1.14 Gallatin–Gros Ventre confining unit

The physical and chemical characteristics of the Gallatin–Gros Ventre confining unit in the WRB are described in this section of the report.

Physical characteristics

The Gallatin–Gros Ventre confining unit is composed of the Cambrian-age Gallatin Limestone and Gros Ventre Formation. The thick unit confines and separates the underlying Flathead aquifer from the overlying Paleozoic aquifer system **(Plate II)**. Reported thickness of the Gallatin Limestone ranges from 0 to about 450 ft, and the thickness of the Gros Ventre Formation ranges from 0 to about 700 ft (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Gallatin Limestone is composed of dense, thinly bedded to massive, glauconitic and oolitic limestone with interbedded shale, silty shale, and thin sandstone beds (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Gros Ventre Formation is composed of limestone, shale, calcareous shale, and a basal flat-pebble conglomerate (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Even though both formations are considered to be confining units, both may yield small quantities of water to wells and springs at some locations in the WRB, especially areas with secondary permeability attributable to joints and fractures (Whitcomb and Lowry, 1968; McGreevy et al., 1969; Richter, 1981, table IV-1). Joints in the hydrogeologic unit provide small quantities of water (generally less than 5 gal/min) to springs along the Wind River Range (Richter, 1981, table IV-1, p. 53). Little hydrogeologic information is available describing the Gallatin–Gros Ventre confining unit, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Gallatin confining unit in the WRB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E1**. The TDS concentration (296 mg/L) indicated that the water was fresh (**Appendix E1**; supplementary data tables). On the basis of the few properties and constituents analyzed for in the one sample, the water was likely suitable for most uses as no concentrations of properties or constituents in water from the Gallatin confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.1.15 Flathead aquifer

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

Physical characteristics

The Flathead aquifer is composed of the Cambrian-age Flathead Sandstone **(Plate II)**. The Flathead aquifer is a major aquifer in the WRB. The Flathead Sandstone consists of pink, reddish-brown, tan and gray, fine- to medium-grained, arkosic and quartzitic sandstone, with some conglomerate and arkose in the lower part (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). The Flathead aquifer is confined by the overlying Gallatin–Gros Ventre confining unit and below by nonporous igneous and metamorphic rocks of the Precambrian basement that act as a basal confining unit to all aquifers and aquifer systems in the WRB **(Plate II)**.

The Flathead Sandstone is present throughout the WRB and ranges from 50 to 200 ft in thickness (Keefer and Van Lieu, 1966; Richter, 1981, table IV-1, and references therein). Water in the Flathead aquifer is semi-confined to confined and likely is under high artesian pressures (Richter, 1981). Shut-in wellhead pressure from an exploratory well in the Lander area was estimated to be as great as 525 psi (Weston Engineering, Inc., 2007b). Porosity is intergranular, but secondary permeability is present along partings between bedding planes and as fractures associated with folds and faults (Richter, 1981, table IV-1). Recharge to the Flathead aquifer likely is from infiltration of precipitation and streamflow losses in outcrop areas. Little hydrogeologic information is available describing the Flathead aquifer, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**. Although considered a potentially very good source of groundwater for development by many investigators, the aquifer is essentially undeveloped as a source of water because of deep burial throughout most of the WRB and the availability of shallower aquifers.

Chemical characteristics

The chemical composition of groundwater in the Flathead Sandstone in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations (37 and 228 mg/L) indicated that the waters were fresh. On the basis of the few properties and constituents analyzed in the two spring samples, the quality of water from the Flathead Sandstone in the WRB is likely suitable for most uses. None of the concentrations of properties or constituents in water from the Flathead aquifer approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Flathead aquifer in the WRB also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F1**. The TDS concentration (2,590 mg/L) indicated that the water was slightly saline. Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in the produced-water sample and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Flathead aquifer in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the constituents analyzed had applicable health-based standards; however, concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs) for domestic use and exceeded State of Wyoming agricultural-use standards. No concentrations of properties or constituents exceeded State of Wyoming livestock standards.

7.1.16 Precambrian basal confining unit

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

Physical characteristics

Undifferentiated nonporous igneous and metamorphic rocks of the Precambrian basement act as a basal confining unit for the Flathead aquifer, as well as for all aquifers and aquifer systems in the WRB **(Plate II)**. Little is known about Precambrian rocks at depth in the WRB; however, wells have been completed locally in this hydrogeologic unit for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out – permeability is attributable to weathered, jointed, fractured, or faulted rocks (Whitcomb and Lowry, 1968; Richter, 1981). Little hydrogeologic information is available for the Precambrian basal confining unit, but available well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Precambrian basal confining unit in the WRB was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations are listed in **Appendix E1**. TDS concentrations (108 and 187 mg/L) indicated that the waters were fresh. On the basis of the few properties and constituents analyzed for in the two spring samples, the quality of water from the Precambrian basal confining unit in the WRB is likely suitable for most uses. No concentrations of properties or constituents in water from the Precambrian basal confining unit approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2 Bighorn Basin

The physical and chemical characteristics of hydrogeologic units in the Bighorn Basin (BHB) are described in this section of the report. These hydrogeologic units are identified on **Plate III**.

7.2.1 Quaternary unconsolidated-deposit aquifers

The physical and chemical characteristics of the Quaternary unconsolidated-deposit aquifers in the BHB are described in this section of the report. Much of the description of the physical characteristics of these aquifers was modified from Bartos et al. (2005).

Physical characteristics

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

Quaternary unconsolidated-deposit aquifers are composed primarily of sand and gravel interbedded with finer-grained sediments such as silt and clay, although coarser deposits such as cobbles and boulders occur locally (Swenson, 1957; Robinove and Langford, 1963; Lowry et al., 1976; Cooley and Head, 1979a,b, 1982; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). These aquifers have small areal extent and primarily occur as alluvium (commonly associated with colluvium and referred to as “alluvial aquifers”) or terrace deposits (sometimes referred to as “gravel, pediment, and sand deposits” in some reports and referred to herein as “terrace-deposit aquifers”) along narrow valleys and in adjacent upland areas, and along streams and rivers in the BHB **(Plates I and III)**. Consequently, many wells completed in Quaternary unconsolidated-deposit aquifers are located close to and along streams and rivers because deposits commonly are less than 1 mile wide near streams in the basin. Along the floodplains, wells completed in alluvial aquifers are likely in hydraulic connection with streams and rivers. Some Quaternary unconsolidated-deposit aquifers are composed of saturated landslide and glacial deposits (Lowry et al., 1976; Libra et al., 1981). Terrace deposits of the BHB are present in many different terrace levels alongside rivers draining the basin

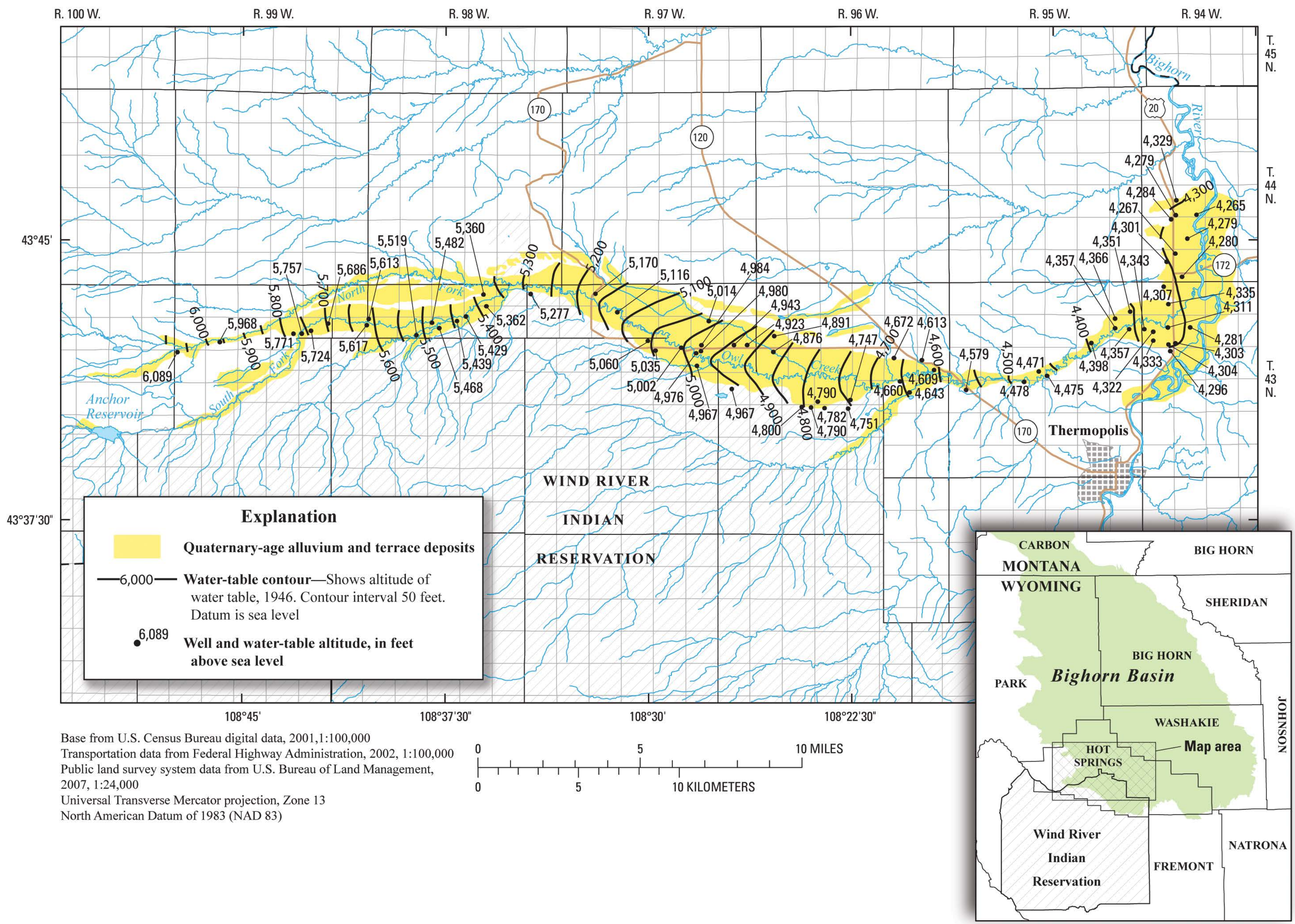


Figure 7-5. Water-table contours in Quaternary unconsolidated-deposit aquifers in Owl Creek Valley, Wyoming (modified from Berry and Littleton, 1961, Plate II).

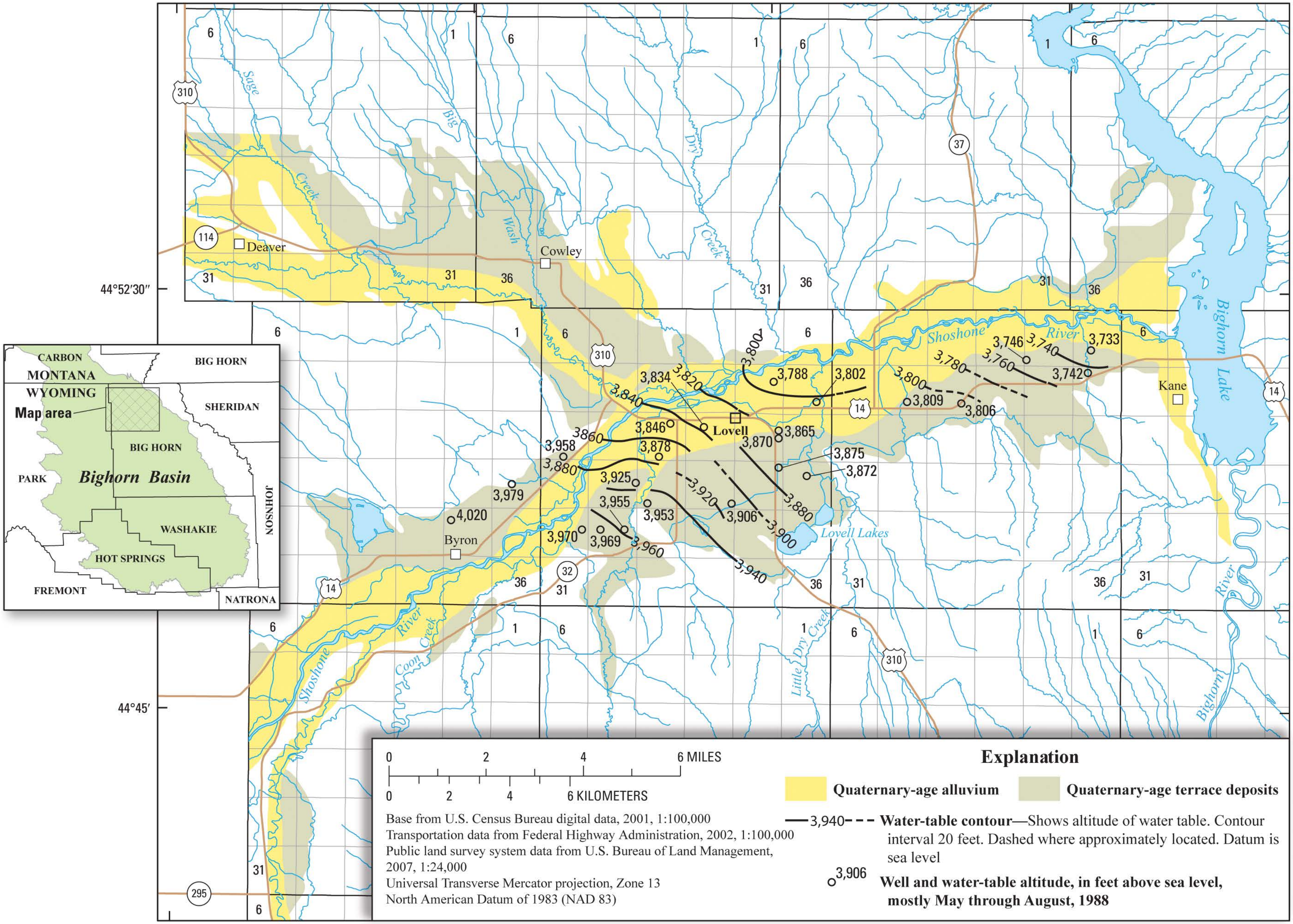


Figure 7-6. Water-table contours in Quaternary alluvial and terrace-deposit aquifers along the Shoshone River, Wyoming (modified from Plafcan et al., 1993, Figure 9).

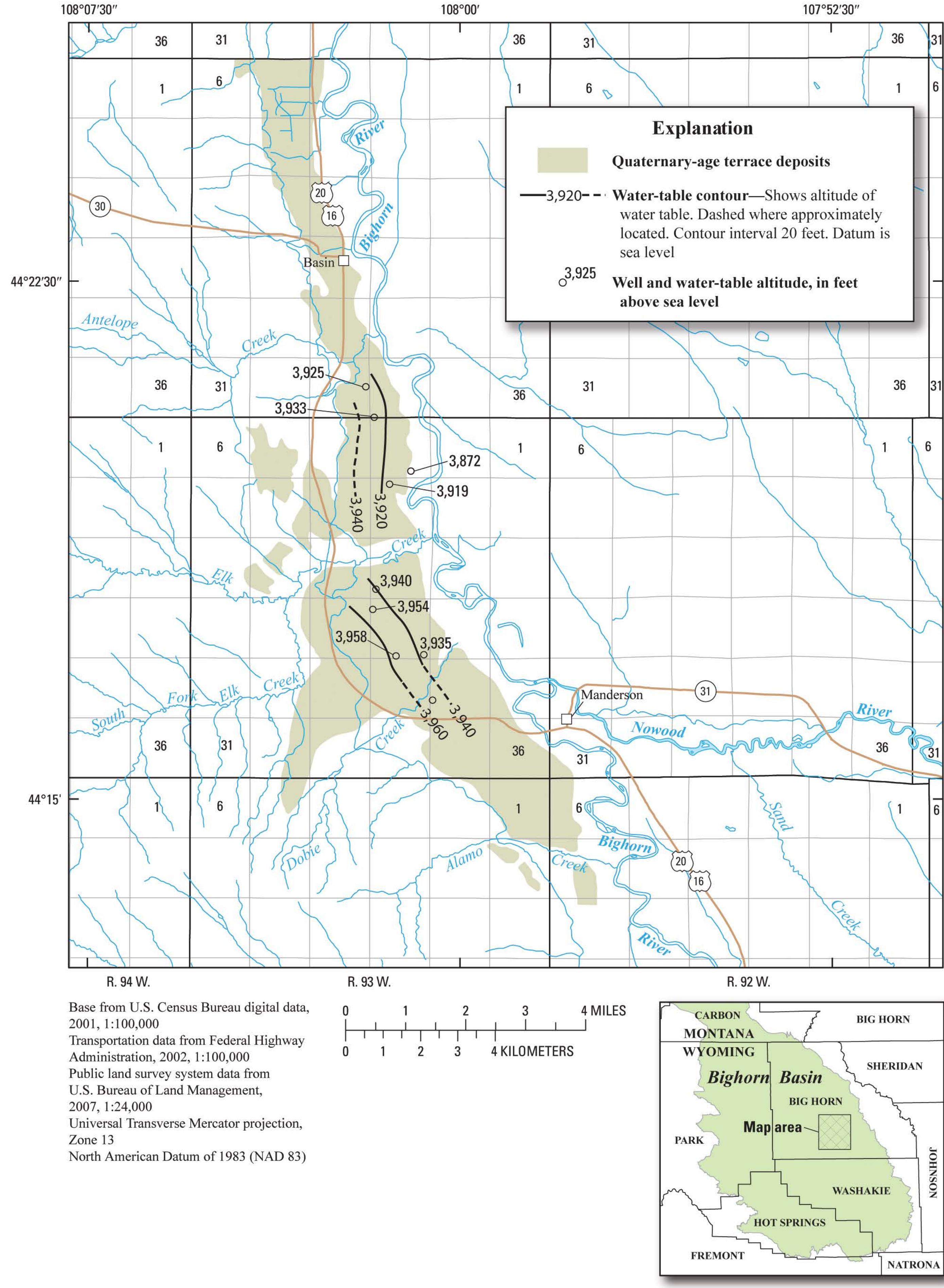


Figure 7-7. Water-table contours in Quaternary terrace-deposit aquifers along Orchard Bench, Wyoming (modified from Plafcan et al., 1993, Figure 10).

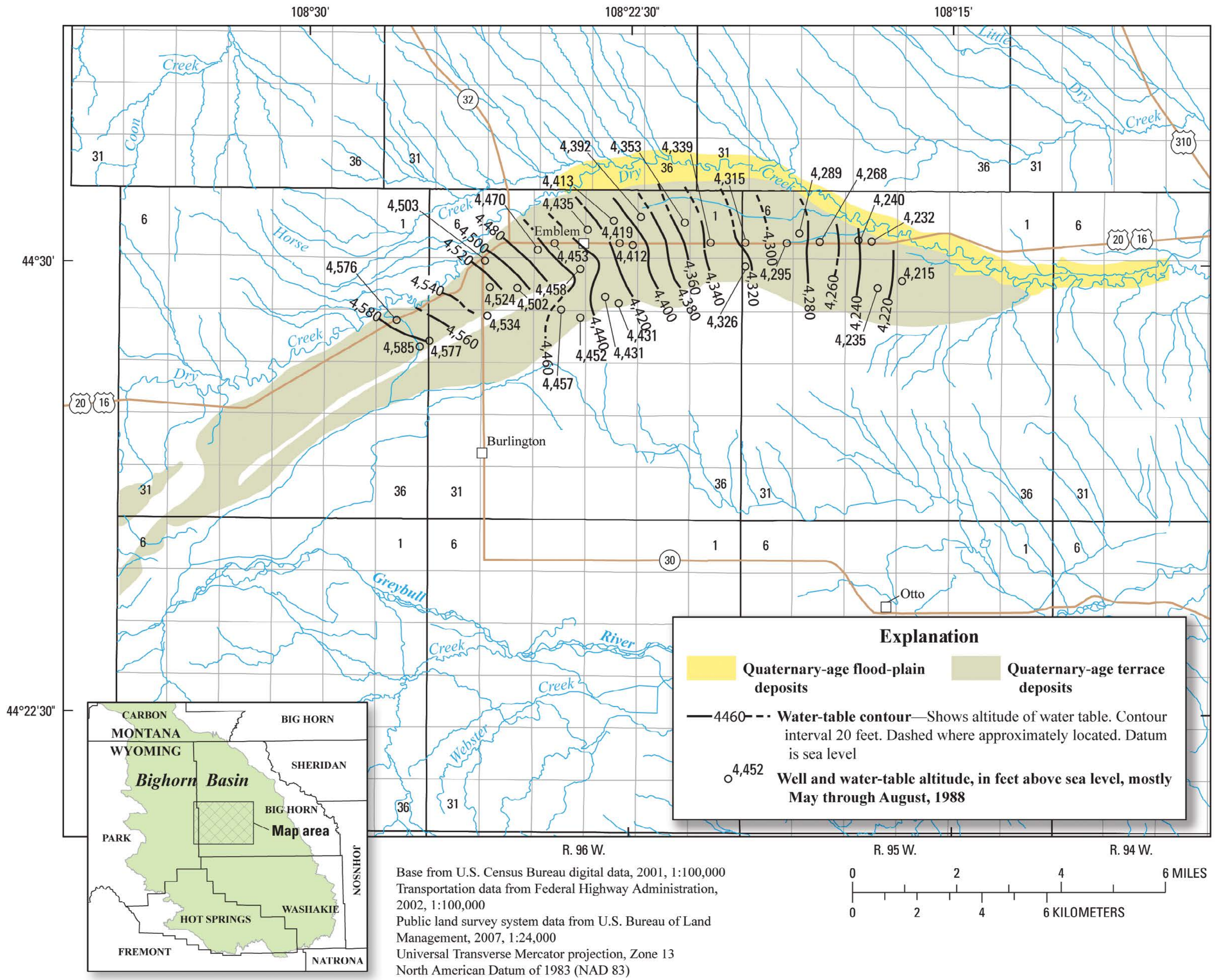
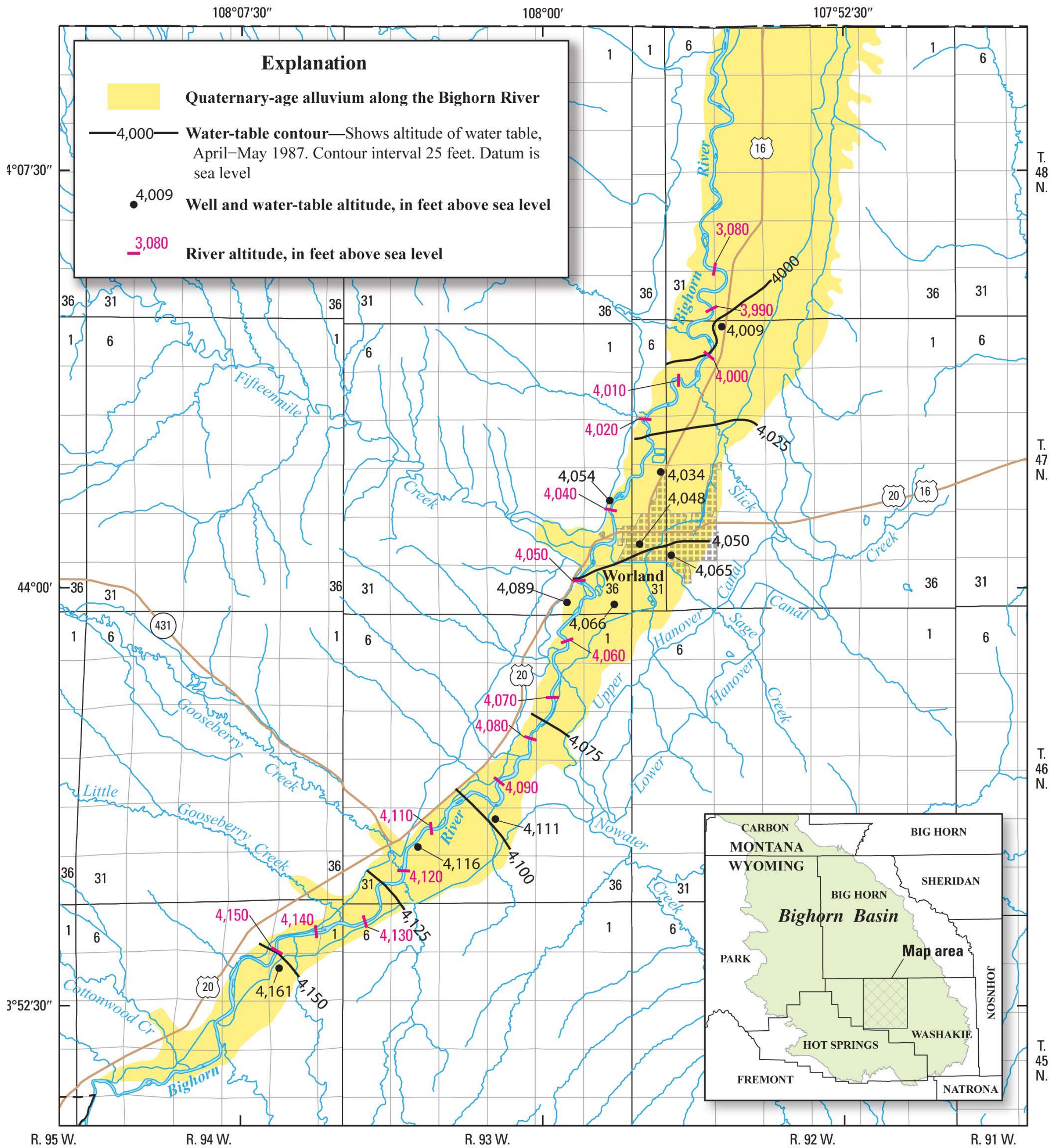


Figure 7-8. Water-table contours in Quaternary terrace-deposit aquifers along Emblem Bench, Wyoming (modified from Plafcan et al., 1993, Figure 11).



Base from U.S. Census Bureau digital data, 2001, 1:100,000
Transportation data from Federal Highway Administration, 2002, 1:100,000
Public land survey system data from U.S. Bureau of Land Management, 2007, 1:24,000
Universal Transverse Mercator projection, Zone 13
North American Datum of 1983 (NAD 83)

Geology modified from Love and Christiansen (1985)

0 2 4 8 MILES
0 2 4 8 KILOMETERS

Figure 7-9. Water-table contours in Quaternary alluvial aquifers along the Bighorn River, Wyoming (modified from Susong et al., 1993, Figure 8).

and in adjacent upland areas. The terrace sequence in the BHB has been studied by many investigators because the sequence is considered to be a model of late Cenozoic erosional history as well as a model of the fluvial history and mechanics of basin rivers (Mackin, 1937, 1947; Moss and Bonini, 1961; Ritter, 1967, 1975; Palmquist, 1978, 1979, 1983; Reheis, 1982; Ritter and Kauffman, 1983).

The thickness of alluvium and terrace deposits in the BHB varies substantially, depending on stream or river valley and location; thickness may be as great as 100 ft, but the thickness of alluvium generally is less than 30 ft and the thickness of terrace deposits generally is less than 50 ft (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976, and references therein; Cooley and Head, 1979a,b, 1982; Libra et al., 1981; Western Water Consultants, Inc., 1983a; McLellan, 1988; Plafcan et al., 1993; Susong et al., 1993; Lidstone and Associates, Inc., 2007b).

Well yield from Quaternary unconsolidated-deposit aquifers varies considerably in the BHB; it is directly related to the size and sorting of material composing a deposit as well as the saturated thickness of the deposit. Well yields are high from aquifers having great saturated thickness and very-coarse grain size. Alluvium derived from mountainous areas generally is coarser than alluvium from formations in the basin (Lowry et al., 1976; Plafcan and Ogle, 1994, Table 5). Hydrogeologic data describing the Quaternary-age unconsolidated deposits (alluvial aquifers, terrace-deposit aquifers, and glacial-deposit aquifers), including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

The areal extent of Quaternary unconsolidated-deposit aquifers coincides with much of the rural population and irrigated cropland in the BHB, so these aquifers are particularly susceptible to contamination from human activities at the land surface. In fact, evidence of groundwater contamination by human activities has been detected as elevated nitrate concentrations and as organic compounds such as volatile organic compounds and pesticides (Plafcan et al., 1993; Susong et al., 1993; Eddy-Miller, 1998a,b; Eddy-Miller and Norris, 2001; Eddy-Miller and Remley, 2005; Bartos et al., 2005, 2009). In a statewide assessment of pesticides in groundwater in Wyoming, the largest percentage of pesticide detections and the largest number of different pesticides detected were in samples from wells in the BHB, many of which were completed in Quaternary unconsolidated-deposit aquifers (Bartos et al., 2009).

Recharge, discharge, and groundwater movement

Recharge to many Quaternary unconsolidated-deposit aquifers is not only from direct infiltration of precipitation and ephemeral and perennial streamflow losses, but also from infiltration of diverted surface water from unlined irrigation canals and ditches, from water applied to fields, and as discharge from underlying aquifers (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Cooley and Head, 1979a,b, 1982; Plafcan et al., 1993). Most unconsolidated terrace deposits in the BHB were not saturated prior to irrigation, indicating that recharge of diverted surface water likely is the dominant source of recharge to terrace-deposit aquifers (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963). Water levels in many terrace-deposit aquifers are directly related to irrigation diversions. During the irrigation season, water levels in these deposits at some locations are the same elevation as water levels in unlined irrigation canals and ditches (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Plafcan et al., 1993). Water levels in terrace-deposit aquifers typically begin to rise some time after irrigation begins (generally March to April in the BHB), continue to rise after irrigation ceases as surface soils continue to drain (generally September to October), and reach maximum water levels in early winter (Swenson and Bach, 1951; Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Plafcan et al., 1993). Consequently, water quality in these terrace-deposit aquifers is likely to vary during the year in response to application of diverted surface water, variation in surface-water quality throughout the irrigation season, and subsequent infiltration and percolation of these waters (Plafcan et al., 1993).

Discharge from Quaternary unconsolidated-deposit aquifers occurs by evapotranspiration, gaining streams, seeps, drains, and spring flows, as well as withdrawals from wells and collection galleries (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). Evapotranspiration from Quaternary unconsolidated-deposit aquifers is likely to be highest in areas where crops are grown (Libra et al., 1981).

Groundwater flow in most Quaternary unconsolidated-deposit aquifers generally is toward rivers or in the direction of streamflow (Swenson, 1957; Berry and Littleton, 1961; Robinove and Langford, 1963; Lowry et al., 1976; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994). Robinove and Langford (1963) reported that that the Greybull River is a gaining stream throughout most of its length. A water-table contour map constructed by Berry and Littleton (1961, Figure 8) indicates that groundwater in the Quaternary unconsolidated-deposit aquifers along the Owl Creek Valley flows toward the river in the direction of streamflow **(Figure 7-5)**. The investigators also noted that the slope of the water table was nearly the same as that of the stream channel (75 feet per mile in the western part and about 30 feet per mile in eastern part), and that Owl Creek generally is a gaining stream but is a losing stream near its confluence with the Bighorn River. A water-table contour map constructed by Plafcan et al. (1993, **Figure 9**) indicates that groundwater in the alluvial aquifers along the Shoshone River near Lovell in Big Horn County flows toward the river, and groundwater in the terrace-deposit aquifers in the same area generally flows in the downstream direction or toward the river **(Figure 7-6)**. Water-table contour maps constructed by Plafcan et al. (1993, **Figures 10 and 11**) indicate that groundwater in the terrace-deposit aquifers along Orchard Bench **(Figure 7-7)** and Emblem Bench **(Figure 7-8)** in Big Horn County generally flows in the downstream direction or toward the river. A water-table contour map constructed by Susong et al. (1993, Figure 8) indicates that groundwater in alluvial aquifers along the Bighorn River flows toward the river in Washakie County **(Figure 7-9)**.

Chemical characteristics

The chemical composition of groundwater from alluvial and terrace-deposit aquifers is evaluated in this section of the report.

Alluvial aquifers

The chemical composition of groundwater in alluvial aquifers in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 109 wells and 3 springs. Summary statistics calculated for available constituents are listed in Appendix E2. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram A). TDS concentrations were highly variable and indicated that about one-half of waters were slightly saline (51 percent), slightly less than one-half of waters were fresh (46 percent), and the remaining waters were moderately saline (**Appendix E2; Appendix G2**, diagram A; supplementary data tables). TDS concentrations ranged from 67 to 9,160 mg/L, with a median of 1,080 mg/L.

Concentrations of some properties and constituents in water from alluvial aquifers in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most of these environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (89 percent of samples analyzed for the constituent), gross alpha radioactivity (38 percent), ammonia (14 percent), nitrate (7 percent), and nitrate plus nitrite (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (80 percent), manganese (67 percent), sulfate (67 percent), filtered iron (22 percent), pH (1 percent above upper limit), and chloride (1 percent).

Concentrations of some properties and constituents in water from alluvial aquifers exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in these environmental water samples that had concentrations greater than agricultural-use standards were sulfate (67 percent), manganese (67 percent), gross alpha radioactivity (38 percent), SAR (16 percent), TDS (9 percent), chloride (5 percent), boron (4 percent), and pH (1 percent above upper limit). Properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (38 percent), sulfate (4 percent), TDS (4 percent), and pH (1 percent above upper limit).

Terrace-deposit aquifers

The chemical composition of groundwater in terrace-deposit aquifers in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 89 wells, one agricultural drain, and three springs. Summary statistics calculated for available constituents are listed in Appendix E2. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram B). TDS concentrations were variable and indicated that most waters were fresh (58 percent of samples) and the remaining waters were slightly to moderately saline (**Appendix E2, Appendix G2;** diagram B; supplementary data tables). TDS concentrations ranged from 265 to 6,360 mg/L, with a median of 879 mg/L.

Concentrations of some properties and constituents in water from terrace-deposit aquifers in the WRB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most of these environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), nitrate (9 percent), nitrate plus nitrite (9 percent), gross alpha radioactivity (8 percent), ammonia (3 percent), and fluoride (2 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (84 percent), sulfate (61 percent), fluoride (14 percent), and manganese (10 percent).

Concentrations of some properties and constituents in water from terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in these environmental water samples that had concentrations greater than agricultural-use standards were sulfate (70 percent), TDS (16 percent), gross alpha radioactivity (8 percent), SAR (5 percent), and chloride (3 percent). Properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (8 percent), sulfate (2 percent), and TDS (2 percent).

7.2.2 White River aquifer and Wagon Bed confining unit

The White River aquifer and Wagon Bed confining unit are composed of the White River and Wagon Bed Formations, respectively. In the BHB, the White River Formation is present only as erosional remnants in the Bighorn Mountains, and the Wagon Bed Formation is present only in the Owl Creek Mountains **(Plate I)**. The White River Formation is classified as an aquifer and the Wagon Bed Formation as a confining unit in the BHB on the basis of hydrogeologic characteristics in the WRB. No water use for these hydrogeologic units has been reported in the BHB. Consequently, the physical and groundwater-quality characteristics of these hydrogeologic units were described previously in the WRB section of this report.

7.2.3 Lower Tertiary/Upper Cretaceous aquifer system

Hydrogeologic units composing the lower Tertiary/Upper Cretaceous aquifer system are described in this section of the report. This large, areally extensive aquifer system coincides with the boundaries of the structural basin proper and is thousands of feet thick in the interior basin. Many domestic and stock wells in the BHB are completed in this aquifer system. Characteristics of individual hydrogeologic units composing the aquifer system and the relation among the units are described.

The lower Tertiary/Upper Cretaceous aquifer system comprises lithostratigraphic units ranging in age from Eocene to Upper Cretaceous **(Plate III)**. The lower Tertiary/Upper Cretaceous aquifer system comprises five hydrogeologic units – the Willwood aquifer, Fort Union aquifer, Lance aquifer, Meeteetse aquifer and confining unit, and Mesaverde aquifer **(Plate III)**. These hydrogeologic units are not separated from one another by any regional confining units. The lower Tertiary/Upper Cretaceous aquifer system is confined below by the thick Cody confining unit, which separates the system from the underlying lower and middle Mesozoic aquifers and confining units **(Plate III)**. The lower Tertiary-age Willwood and Fort Union Formations, which contain the Willwood and Fort Union aquifers, respectively, generally are flat lying to gently dipping and crop out within the basin interior **(Plate I)**, whereas the Upper Cretaceous-age Lance, Meeteetse, and Mesaverde Formations, which contain the Lance aquifer, Meeteetse aquifer and confining unit, and Mesaverde aquifer, respectively, dip basinward and crop out near basin margins.

Individual sandstone beds compose the aquifers in the lower Tertiary/Upper Cretaceous aquifer system. The sandstone beds composing the aquifers are interbedded and commonly separated by fine-grained rocks with low hydraulic conductivity (shale, mudstone, claystone, or siltstone). Consequently, water in the sandstone aquifers likely is under various degrees of confinement and hydraulic connection or isolation. Well yields from the hydrogeologic units are directly related to the number and combined thickness of sandstone lenses or beds ("aquifers" or "subaquifers") penetrated (Lowry et al., 1976; Libra et al., 1981). Small well yields and highly variable (and commonly poor) water quality limit most uses to domestic and stock purposes.

7.2.3.1 Willwood and Fort Union aquifers

The physical and chemical characteristics of the Willwood and Fort Union aquifers in the BHB are described in this section of the report. The aquifers are described together in this report because they are nearly indistinguishable in the BHB. Much of this description of the physical characteristics of the Willwood and Fort Union aquifers was modified from Bartos et al. (2005).

Physical characteristics

The Paleocene-age Fort Union Formation comprises the Fort Union aquifer, and the Eocene-age Willwood Formation comprises the Willwood aquifer in the BHB **(Plate III)**. The aquifers are the uppermost hydrogeologic units in the lower Tertiary/Upper Cretaceous aquifer system. The Fort Union Formation is underlain by the Lance Formation **(Plate III)**. Many wells are installed in the aquifers because the Willwood and Fort Union Formations are at or near land surface throughout much of the basin; however, most wells are for stock and domestic use because of relatively low yield and variable water quality that precludes some uses without treatment (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993; Plafcan and Ogle, 1994).

The Fort Union and Willwood Formations have many similar characteristics, and it is very difficult to distinguish one formation from another, especially in the subsurface (Keefer et al., 1998). Both formations are areally extensive **(Plate I)** and are composed primarily of fine- to coarse-grained sandstone beds interbedded with shale and other fine-grained rocks, locally with some conglomerate and coal deposits. Individual sandstones are sheet or channel sandstones that vary widely in geometry and thickness in the BHB (see for example Neasham and Vondra, 1972; Bown, 1975). Many channel sandstones in the Willwood Formation are ribbon sandstones (also known as "shoestring" sandstones) of very narrow width and thickness (generally less than about 10 ft in thickness) (Kraus, 2001, and references therein). The Fort Union Formation is primarily exposed along the basin margins, whereas the Willwood Formation is exposed throughout the central part of the basin **(Plate I)**. The Fort Union Formation unconformably underlies the Willwood Formation around the margins of the BHB, although the two formations probably are conformable in the structurally deepest parts of the basin (Keefer et al., 1998). In most locations in the BHB, the Willwood Formation is highly variegated, but the presence or absence of this characteristic is not a criterion for differentiating it from the Fort Union Formation, even though many earlier investigators used this characteristic to differentiate the two formations (Keefer et al., 1998, and references therein).

On the basis of measured surface sections, the proportion of sandstone to fine-grained rocks in the Fort Union Formation (and by inference, the Willwood Formation) varies greatly by location and sequence examined (Roberts, 1998, and references therein). Lowry et al. (1976) reported that the average proportion of sandstone in the Willwood and Fort Union Formations, on the basis of driller's logs, ranged from 3 to 88 percent with a weighted average of about 25 percent. The reported thicknesses of both formations vary depending on location and whether measured surface sections or subsurface data are used. Estimates of maximum thickness of the Fort Union Formation vary widely, and, using measured surface sections or subsurface methods, range from 1,000–1,500 ft along the east and south basin margins to nearly 7,500–11,500 ft in the structurally deepest parts of the basin along the west or northwest basin margins (Hewett, 1926; Stow, 1938; Rogers et al., 1948; Pierce, 1948; Moore, 1961; Horn, 1963; Hickey, 1980; Keefer et al., 1998; Taylor, 1998). Estimates of the maximum thickness of the Willwood Formation in selected locations range from about 800 ft to nearly 5,000 ft (Van Houten, 1944; Neasham and Vondra, 1972; Gingerich, 1983; Keefer et al., 1998). The formations generally increase in thickness from east to west, and maximum thickness occurs in the structurally deepest parts of the basin along the western margin.

Individual sandstone beds in the Fort Union and Willwood Formations compose the main aquifers; in many cases, these beds are relatively thin, lenticular, and discontinuous. Sandstone beds composing the aquifers are interbedded and commonly separated by fine-grained rocks with low hydraulic conductivity such as shale, mudstone, or siltstone. Consequently, water in the sandstone aquifers likely is under varying degrees of confinement and hydraulic isolation. Water-table conditions may exist in the shallowest sandstones, and semiconfined or confined conditions are likely in deeper sandstones. In general, fine-grained sedimentary rocks (for example, siltstone, shale) in both formations are not likely to yield sufficient quantities of water to be considered aquifers, even though they may be saturated; static water levels in wells completed in the fine-grained rocks may be the same as in adjacent beds of sandstone. Well yields from both aquifers are directly related to the number and thickness of sandstone lenses or beds ("aquifers") penetrated (Lowry et al., 1976; Libra et al., 1981). Median combined spring and well yields for both aquifers are less than 10 gal/min **(Plate IX)**. Although not highly permeable, both aquifers are important sources of water because of their wide areal extent at or near the land surface in the BHB and because enough water can usually be obtained for domestic or stock purposes (but quality varies widely). Hydrogeologic data describing the Willwood and Fort Union aquifers, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Similarly to the Quaternary unconsolidated-deposit aquifers, the areal extent of the Willwood and Fort Union aquifers coincides with much of the rural population and irrigated cropland in the BHB, making these aquifers susceptible to contamination from human activities at the land surface. In fact, evidence of groundwater contamination by human activities has been detected as elevated nitrate concentrations and as organic compounds such as volatile organic compounds and pesticides (Plafcan et al., 1993; Susong et al., 1993; Eddy-Miller, 1998a,b; Eddy-Miller and Norris, 2001; Eddy-Miller and Remley, 2005; Bartos et al., 2005, 2009). Some of these contaminants may be transported to the Willwood and Fort Union aquifers where overlain by Quaternary-age unconsolidated deposits. In a statewide assessment of pesticides in Wyoming groundwater, the largest percentage of pesticide detections and the largest number of different pesticides detected were in samples from wells in the BHB, some of which were completed in the Willwood and Fort Union aquifers (Bartos et al., 2009).

Chemical characteristics

The chemical composition of groundwater from the Willwood and Fort Union aquifers is described in this section of the report.

7.2.3.1.1 Willwood aquifer

The chemical composition of groundwater in the Willwood aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 92 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram C). TDS concentrations were variable and indicated that about one-half the waters were slightly saline (51 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram C; supplementary data tables). TDS concentrations ranged from 352 to 9,000 mg/L, with a median of 1,350 mg/L.

Concentrations of some properties and constituents in water from the Willwood aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (100 percent of samples analyzed for the constituent), ammonia (33 percent), molybdenum (15 percent), gross alpha radioactivity (14 percent), selenium (12 percent), nitrate plus nitrite (11 percent), uranium (10 percent), antimony (8 percent), cadmium (6 percent), and fluoride (4 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (96 percent), sulfate (74 percent), manganese (26 percent), fluoride (33 percent), pH (16 percent above upper limit), aluminum (10 percent exceeded lower and upper limits), filtered iron (5 percent), and chloride (4 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in these environmental water samples measured at concentrations greater than agricultural-use standards were SAR (80 percent), sulfate (74 percent), chloride (26 percent), TDS (24 percent), selenium (18 percent), gross alpha radioactivity (14 percent), manganese (5 percent), and pH (1 percent above upper limit). Properties and constituents measured at concentrations greater than livestock-use standards were selenium (18 percent), pH (16 percent above upper limit), gross alpha radioactivity (14 percent), sulfate (2 percent), and TDS (2 percent).

7.2.3.1.2 Fort Union aquifer

The chemical composition of groundwater in the Fort Union aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 31 wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram D). TDS concentrations were variable and indicated that the water ranged from fresh to moderately saline (**Appendix E2; Appendix G2**, diagram D; supplementary data tables). TDS concentrations ranged from 372 to 4,920 mg/L, with a median of 1,550 mg/L.

The chemical composition of groundwater in the Fort Union aquifer also was characterized and the quality evaluated on the basis of one produced-water sample from a well. Summary statistics calculated for available constituents are listed in **Appendix F2**. The TDS concentration (1,610 mg/L) from the produced-water sample indicated that the water was slightly saline (Appendix F2; supplementary data tables).

Concentrations of some properties and constituents in water from the Fort Union aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): radon-222 (80 percent of samples analyzed for the constituent), ammonia (50 percent), gross alpha radioactivity (14 percent), and fluoride (3 percent). Concentrations of several properties and constituents exceeded aesthetic standards (SMCLs) for domestic use: TDS (97 percent), sulfate (78 percent), filtered iron (30 percent), manganese (30 percent), fluoride (28 percent), chloride (9 percent), and pH (6 percent above upper limit).

Chemical analyses were available for only a few properties and constituents from one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of TDS and sulfate that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (81 percent), SAR (65 percent), TDS (41 percent), mercury (20 percent), chloride (19 percent), gross alpha radioactivity (14 percent), manganese (10 percent), selenium (7 percent), and boron (5 percent). One constituent and one property had concentrations greater than livestock-use standards: gross alpha radioactivity (14 percent) and pH (6 percent above upper limit).

The produced-water sample had a concentration of one constituent that exceeded agricultural-use standards: sulfate. No properties or constituents in the produced-water sample exceeded livestock-use standards.

7.2.3.2 Lance aquifer

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

Physical characteristics

The Upper Cretaceous-age Lance Formation comprises the Lance aquifer in the BHB **(Plate III)**. The aquifer is part of the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Lance aquifer consists of sandstone interbedded with shale, claystone, siltstone, and thin coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the aquifer in the BHB ranges from 800 ft in the southwest to 1,800 ft in the north (Lowry et al., 1976; Libra et al., 1981, Table IV-1). The Lance Formation is overlain by the Fort Union Formation and underlain by the Meeteetse Formation **(Plate III)**. Confined conditions predominate in the Lance aquifer, but unconfined (water-table) conditions are likely in outcrop areas of the Lance Formation. Sandstone beds within the aquifer have been developed for stock, domestic, and limited public-supply use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. Many of the lenticular, laterally discontinuous sandstones are confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Lance aquifer, including well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Lance aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from eight wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (88 percent of samples) and the remaining waters were slightly saline (Appendix E2; supplementary data tables). TDS concentrations ranged from 591 to 1,260 mg/L, with a median of 902 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations from produced-water samples were variable and ranged from slightly to moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,210 to 4,880 mg/L, with a median of 1,760 mg/L.

Concentrations of some properties and constituents in water from the Lance aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): fluoride (29 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), fluoride (57 percent), pH (50 percent above upper limit), and sulfate (38 percent).

For the water-quality analyses from produced-water samples, chemical analyses of many properties and constituent analyses were not available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), pH (50 percent above upper limit), chloride (33 percent), and sulfate (33 percent).

Concentrations of some properties and constituents in water from the Lance aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (60 percent), sulfate (50 percent), and chloride (12 percent). The property that had values greater than livestock-use standards was pH (50 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (100 percent), chloride (67 percent), and TDS (33 percent). The produced-water samples generally had values of one property that exceeded livestock-use standards: pH (50 percent above upper limit).

7.2.3.3 Meeteetse aquifer and confining unit

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

Physical characteristics

The Upper Cretaceous-age Meeteetse Formation, and, in places, tongues of the Upper Cretaceous-age Lewis Shale, compose the Meeteetse aquifer and confining unit in the BHB **(Plate III)**. The aquifer is part of the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Meeteetse confining unit and aquifer consists of lenticular, clayey to silty, fine-grained, poorly indurated sandstone interbedded with shale, claystone, siltstone, bentonite, and sparse thin coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Where present, the Lewis Shale is interbedded with the Meeteetse Formation and acts as a confining unit **(Plate III)**. Consequently, the hydrogeologic unit is considered both a confining unit and aquifer herein. The reported thickness of the hydrogeologic unit in the BHB ranges from 650 ft in the southeast to 1,200 ft in the northwest (Lowry et al., 1976; Libra et al., 1981, table IV-1). The Meeteetse Formation is overlain by the Lance Formation and underlain by the Mesaverde Formation **(Plate III)**. Confined conditions predominate, but unconfined (water-table) conditions are likely in outcrop areas. Sandstone beds within the aquifer have potential for development for stock and domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. The lenticular, laterally discontinuous sandstones are often confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Meeteetse confining unit and aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Meeteetse confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (60 percent of samples) and the remaining waters were fresh (**Appendix E2; supplementary data tables**). TDS concentrations ranged from 936 to 1,400 mg/L, with a median of 1,200 mg/L.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples indicated that most waters were slightly saline (67 percent of samples) and the remaining water was moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,150 to 5,520 mg/L, with a median of 2,300 mg/L.

Concentrations of some properties and constituents in the Meeteetse confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (60 percent), filtered iron (33 percent), manganese (33 percent), and pH (20 percent above upper limit).

For the three produced-water samples, chemical analyses for many properties and constituents were not available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards are limited. One produced-water sample had concentrations of one constituent that exceeded health-based standards (USEPA MCLs): fluoride. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: chloride (100 percent), TDS (100 percent), filtered iron (100 percent), fluoride (50 percent), and pH (33 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. One constituent and one property in environmental water samples had concentrations greater than agricultural-use standards: sulfate (100 percent) and SAR (20 percent). One property (pH) had values greater than livestock-use standards (20 percent above upper limit).

The three produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), chloride (100 percent), and TDS (100 percent). Some produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (33 percent above upper limit) and TDS (33 percent).

7.2.3.4 Mesaverde aquifer

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

Physical characteristics

The Upper Cretaceous-age Mesaverde Formation comprises the Mesaverde aquifer in the BHB **(Plate III)**. The aquifer is the lowermost hydrogeologic unit in the lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The Mesaverde aquifer consists of a variable sequence of massive, lenticular, fine- to coarse-grained sandstone, carbonaceous shale, and lesser amounts of coal (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The sandstones commonly are lenticular and laterally discontinuous, and range in thickness from 5 to 40 ft (Plafcan et al., 1993). The lowermost part of the formation, known as the "Eagle Sandstone," consists primarily of fine-grained sandstone and shaley sandstone. The reported thickness of the Mesaverde Formation ranges from 900 ft in the eastern BHB to 1,800 ft in the south-central BHB (Libra et al., 1981, Table IV-1). The Mesaverde aquifer generally is confined above by the Meeteetse aquifer and confining unit and is confined below by the Cody confining unit **(Plate III)**. Confined conditions predominate, and unconfined (water-table) conditions are likely in outcrop areas of the Mesaverde Formation. Sandstone beds within the aquifer have potential for development for stock, domestic, or limited public-supply use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993; Susong et al., 1993), although the poor water quality determined during this study would preclude most uses without treatment. The lenticular, laterally discontinuous sandstones commonly are confined by fine-grained lithologies (siltstone, claystone, and shales); this results in a sequence of subaquifers (Libra et al., 1981). Hydrogeologic data describing the Mesaverde aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Mesaverde aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 24 wells and two springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram E). TDS concentrations were variable and indicated that most waters were slightly saline (73 percent of samples) and the remaining waters were fresh to moderately saline (**Appendix E2; Appendix G2**, diagram E; supplementary data tables). TDS concentrations ranged from 395 to 5,510 mg/L, with a median of 1,770 mg/L.

The chemical composition of groundwater in the Mesaverde aquifer also was characterized and the quality evaluated on the basis of 21 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram A). TDS concentrations from produced-water samples were variable and ranged from fresh to moderately saline, and most waters were slightly saline (76 percent) (**Appendix F2; Appendix H2,** diagram A; supplementary data tables). TDS concentrations ranged from 965 to 7,400 mg/L, with a median of 2,390 mg/L.

Concentrations of some properties and constituents in water from the Mesaverde aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): gross alpha radioactivity (100 percent of samples analyzed for the constituent) and boron (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (96 percent), sulfate (81 percent), manganese (43 percent), filtered iron (29 percent), fluoride (8 percent), and chloride (4 percent).

Some water-quality analyses were available from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): boron (100 percent) and fluoride (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), chloride (60 percent), fluoride (50 percent), manganese (50 percent), sulfate (20 percent), and pH (14 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (100 percent), sulfate (85 percent), mercury (60 percent), TDS (38 percent), SAR (29 percent), chloride (12 percent), and boron (11 percent). Properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (100 percent), TDS (4 percent), and sulfate (4 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), boron (100 percent), chloride (80 percent), TDS (76 percent), and sulfate (27 percent). The produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (14 percent above upper limit) and TDS (5 percent).

7.2.3.4.1 Eagle Sandstone

The chemical composition of groundwater in the Eagle Sandstone in the BHB was characterized and the quality evaluated on the basis of one produced-water sample from a well. The TDS concentration (3,680 mg/L) indicated that the water was moderately saline.

Concentrations of some characteristics and constituents in the Eagle Sandstone in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, and many characteristic and constituent analyses were not available and could not be compared with health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards. The produced-water sample had concentrations of one characteristic (TDS) and one constituent (sulfate) that exceeded aesthetic standards for domestic use.

For agricultural and livestock use, concentrations of some characteristics and constituents exceeded State of Wyoming standards in the BHB. The produced-water sample had concentrations of two constituents that exceeded agricultural-use standards: chloride and sulfate. The produced-water sample had no concentrations of characteristics or constituents that exceeded livestock-use standards.

7.2.3.5 Recharge, discharge, and groundwater movement

Recharge to the Willwood and Fort Union aquifers likely is primarily from areal infiltration and percolation of precipitation in outcrop areas, and from localized recharge beneath ephemeral drainages during periods of runoff. Recharge also is likely in areas where the Willwood and Fort Union Formations are overlain by saturated Quaternary unconsolidated deposits (alluvium and terrace deposits) (Swenson, 1957; Berry and Littleton, 1961; Lowry et al., 1976).

Recharge to aquifers in Upper Cretaceous-age lithostratigraphic units likely is primarily from infiltration and percolation of precipitation in outcrop areas, and from localized recharge beneath ephemeral drainages during periods of runoff (Swenson, 1957; Berry and Littleton, 1961). Recharge in outcrop areas likely is largest where sandstone beds dipping toward the basin interior are exposed along basin margins (Berry and Littleton, 1961). The sandstone beds (aquifers) commonly are confined by interbedded shales with much lower permeability, resulting in development of confined conditions as water moves downgradient. In places, fractures may provide hydraulic connection between confined sandstone aquifers and allow for movement of water between them (Berry and Littleton, 1961). Berry and Littleton also noted that hydraulic connection between confined sandstone aquifers due to pressure head differential alone was possible even when fractures were not present, depending on confining unit permeability, thickness, and areal extent.

Discharge from the lower Tertiary/Upper Cretaceous aquifer system is both natural and anthropogenic. Groundwater discharges through seeps, springs, interformational movement, and gaining streams (Lowry et al., 1976; Libra et al., 1981). Lowry et al. (1976, Sheet 1) also noted that perennial streamflow gains and losses associated with discharge from and recharge to the Willwood and Fort Union aquifers in the center of the basin "is not great enough to be discernible from other minor factors affecting streamflow, such as evapotranspiration." The primary anthropogenic sources of discharge from the lower Tertiary/Upper Cretaceous aquifer system are domestic, stock, and oil and gas wells.

Potentiometric-surface maps of aquifers in the lower Tertiary/Upper Cretaceous aquifer system in the BHB have not been constructed, and regional groundwater flow has not been described. The discontinuous and lenticular characteristic of the sandstones composing the aquifers makes it difficult to create and interpret such maps (Libra et al., 1981). In addition, the sandstones are interbedded with fine-grained rocks, and the amount of hydraulic connection between individual sandstone aquifers is difficult to assess. However, the authors suspect that groundwater flow in the shallow aquifers is primarily local and related to topography, with discharge occurring in some areas along streams adjacent to local recharge areas. The amount of regional groundwater flow and the relation between local and possible intermediate and regional groundwater flow are unknown.

7.2.4 Cody confining unit

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

Physical characteristics

The regionally extensive Cody confining unit is composed of the Upper Cretaceous-age Cody Shale. This thick unit confines and separates the underlying lower and middle Mesozoic aquifers and confining units from the overlying lower Tertiary/Upper Cretaceous aquifer system **(Plate III)**. The reported thickness of the Cody confining unit ranges from about 2,100 ft in the northwest to 3,000 ft in the southeastern Bighorn Basin (Lowry et al., 1976; Libra et al., 1981). The upper part of the Cody Shale is composed of gray sandy shale interbedded with shaley sandstone, and the lower part is composed predominantly of dark gray marine shale with some glauconitic sandstone and thin beds of bentonite (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Sandstones and fractured zones in the Cody confining unit yield small quantities of water to wells at some locations in the BHB, although poor water quality limits most uses (Libra et al., 1981; Western Water Consultants Inc., 1982a,b, 1983b, 1986; Plafcan et al., 1993; Susong et al., 1993). Little hydrogeologic information is available describing the Cody confining unit, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Cody confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram F). TDS concentrations were variable and indicated that one-half of the waters were slightly saline (50 percent of samples) and the remaining waters were fresh or moderately saline **(Appendix E2; Appendix G2**, diagram F; supplementary data tables). TDS concentrations ranged from 660 to 8,290 mg/L, with a median of 2,350 mg/L.

The chemical composition of groundwater in the Cody confining unit also was characterized and the quality evaluated on the basis of five produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from fresh to moderately saline, and most of the waters were slightly saline (60 percent) (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,440 to 6,750 mg/L, with a median of 2,940 mg/L.

Concentrations of some properties and constituents in water from the Cody confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): boron (29 percent of samples analyzed for the constituent) and nitrate plus nitrite (14 percent). Concentrations of several properties and constituents

exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (80 percent), manganese (33 percent), chloride (20 percent), fluoride (20 percent), and pH (11 percent above upper limit).
Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), pH (60 percent above upper limit), sulfate (60 percent), and chloride (40 percent).

Concentrations of some properties and constituents in water from the Cody confining unit exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (90 percent), SAR (70 percent), boron (57 percent), TDS (50 percent), copper (50 percent), mercury (50 percent), manganese (33 percent), chloride (30 percent), selenium (17 percent), and pH (11 percent above upper limit). Properties and constituents that had concentrations greater than livestock-use standards were TDS (20 percent), sulfate (20 percent), and pH (11 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (100 percent), chloride (40 percent), and sulfate (60 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: pH (60 percent above upper limit), TDS (20 percent), and chloride (20 percent).

7.2.5 Lower and middle Mesozoic aquifers and confining units

The lower and middle Mesozoic aquifers and confining units is a stratigraphic and hydrogeologic sequence that "consists of impermeable shales that isolate discrete water-bearing sandstone and carbonate units" (Libra et al., 1981, p. 58). Rocks composing the lower and middle Mesozoic aquifers and confining units range in age from Lower Triassic to Upper Cretaceous **(Plate III)**. Although classified as confining units, shales within the sequence "may have enhanced permeabilities in fractured zones, along bedding planes, and within coarser clastic beds" (Libra et al., 1981, p. 58, and references therein). The complex intertonguing and interfingering between the various facies within the sequence creates numerous small permeable zones that function as individual aquifers (or subaquifers). In addition, many of the lithostratigraphic units within this sequence consist of more than one facies, some of which function as confining units (shales and siltstones) and some of which function as aquifers (sandstones and carbonate). Consequently, several of the hydrogeologic units have been defined herein as both aquifer and confining unit **(Plate III)**.
Excluding the numerous oil wells completed in the lower and middle Mesozoic aquifers and confining units, the relatively few wells completed in the hydrogeologic sequence are located primarily in outcrop areas around the basin margin where drilling depth is relatively shallow and waters are relatively fresh. Most of these wells are completed for domestic or stock purposes. Most geologic and hydrogeologic data for the lower and middle Mesozoic aquifers and confining units were generated during petroleum exploration. Groundwater in many of the hydrogeologic units is highly mineralized and unsuitable for most uses.

7.2.5.1 Frontier aquifer

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

Physical characteristics

The Upper Cretaceous-age Frontier Formation comprises the Frontier aquifer in the BHB. The Frontier aquifer consists of lenticular, fine- to medium-grained, argillaceous sandstone, and lenticular conglomeratic sandstone beds, interbedded with shale and lesser amounts of lignite and bentonite (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the aquifer in the BHB ranges from 450 ft in the west to 700 ft in the southeast (Libra et al., 1981, table IV-1). Lowry et al. (1976, Sheet 1) reported that the Frontier Formation contains less than 50 percent sandstone in the basin. The Frontier aquifer is confined above by the thick, regional Cody confining unit and below by the Mowry–Thermopolis confining unit **(Plate III)**. Confined conditions predominate, but unconfined (water-table) conditions have been reported in outcrop areas in the northeastern BHB (Western Water Consultants, Inc., 1982a,b). Permeability is primarily intergranular and dependent on clay content, swelling and floculating properties of the clay minerals, and fluid salinity (Baptist et al., 1952). Recharge to the Frontier aquifer likely is by direct infiltration of precipitation on outcrop areas.

Sandstone beds within the aquifer are considered to have some potential for development, although yields are likely to be small and adequate only for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Western Water Consultants, Inc. (1982a,b) evaluated the Frontier Formation as a potential source of public supply in the northeastern BHB. They defined the lenticular interbedded sandstones in the Frontier Formation as subaquifers, but noted that development potential as a source of public supply was poor because of the low permeability, variable thickness, and the discontinuous nature of sandstone beds.

Chemical characteristics

The chemical composition of groundwater in the Frontier aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from nine wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram G). TDS concentrations were variable and indicated that most waters were slightly saline (58 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram G; supplementary data tables). TDS concentrations ranged from 758 to 5,210 mg/L, with a median of 1,530 mg/L.

The chemical composition of groundwater in the Frontier aquifer also was characterized and the quality evaluated on the basis of 133 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram G). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny, and indicated that most of the water was moderately saline (60 percent) (**Appendix F2; Appendix H2**, diagram B; supplementary data tables). TDS concentrations ranged from 1,470 to 81,800 mg/L, with a median of 6,630 mg/L.

Concentrations of some properties and constituents in water from the Frontier aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): boron (10 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (83 percent), pH (50 percent above upper limit), filtered iron (20 percent), manganese (20 percent), and fluoride (17 percent).

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): boron (100 percent) and fluoride (17 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples), filtered iron (100 percent), chloride (79 percent), fluoride (67 percent), sulfate (46 percent), and pH (19 percent above upper limit). TDS concentrations in 20 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Frontier aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (92 percent), SAR (67 percent), boron (60 percent), mercury (50 percent), pH (25 percent above upper limit), and TDS (25 percent). Properties and constituents measured at concentrations greater than livestock-use standards were pH (50 percent above upper limit), sulfate (8 percent), and TDS (8 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: SAR (100 percent), boron (100 percent), chloride (95 percent), TDS (92 percent), sulfate (47 percent), filtered iron (23 percent), and pH (1 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (65 percent), chloride (52 percent), boron (20 percent), pH (19 percent above upper limit), and sulfate (4 percent).

7.2.5.2 Mowry–Thermopolis confining unit

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

Physical characteristics

The Mowry–Thermopolis confining unit is composed primarily of the the Upper Cretaceous-age Mowry Shale and the Lower Cretaceous-age Thermopolis Shale, but also contains the Lower Cretaceous-age Muddy Sandstone **(Plate III)**. The Mowry Shale is a confining unit that consists of thin-bedded, resistant/brittle shale, with thin sandstone and bentonite beds in the upper part (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Muddy Sandstone comprises the Muddy Sandstone aquifer, which is confined above by the Thermopolis Shale and below by the Mowry Shale **(Plate III)**. The Muddy Sandstone (formerly considered a member of the Thermopolis Shale) is composed of massive sandstone interbedded with mudstone, siltstone, shale, bentonite, and some conglomerate (Paull, 1962; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Thermopolis Shale is a confining unit that consists of soft black shale with sandy, silty, and bentonitic zones

(Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the Mowry–Thermopolis confining unit, including the Muddy Sandstone aquifer, is greater than 700 ft in the BHB (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The reported thickness of the Muddy Sandstone aquifer ranges from 10 to 50 ft (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b; Plafcan et al., 1993). The Mowry–Thermopolis confining unit confines and separates the underlying Cloverly aquifer from the overlying Frontier aquifer **(Plate III)**.

With the exception of oil wells, relatively few wells are installed in the Mowry–Thermopolis confining unit; development is limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Although the Mowry and Thermopolis Shales are confining units, both yield small quantities of water to wells and springs at some locations in the BHB, especially from brittle, fractured shales or sandy zones (Lowry et al., 1976; Libra et al., 1981). The poor water quality determined during this study would preclude most uses without treatment. Most information describing the formations is from oil-field data. Hydrogeologic information available describing the Mowry–Thermopolis confining unit, including well-yield and spring-discharge measurements and other hydraulic properties for all three lithostratigraphic units composing it, are summarized on **Plate IX**.

Chemical characteristics

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

7.2.5.2.1 Mowry confining unit

The chemical composition of groundwater in the Mowry confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from four wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were highly variable and indicated that waters ranged from fresh to very saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 362 to 19,200 mg/L, with a median of 1,150 mg/L.

The chemical composition of groundwater in the Mowry confining unit also was characterized and the quality evaluated on the basis of five produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were moderately saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 1,080 to 7,950 mg/L, with a median of 1,820 mg/L.

Concentrations of some properties and constituents in water from the Mowry confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): fluoride (29 percent of samples analyzed for the constituent) and boron (20 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (86 percent), sulfate (71 percent), filtered iron (33 percent), manganese (33 percent), and fluoride (29 percent). TDS concentrations in 14 percent of environmental water samples exceeded State of Wyoming Class IV standards.

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples), chloride (40 percent), and pH (20 percent above upper limit).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the WRB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (86 percent), SAR (43 percent), TDS (43 percent), boron (20 percent), and chloride (14 percent). One constituent and one property had concentrations greater than livestock-use standards: sulfate (14 percent) and TDS (14 percent).

The produced-water samples generally had concentrations of one constituent and one property that exceeded agricultural-use standards: chloride (40 percent) and TDS (40 percent). Some produced-water samples had concentrations of two properties that exceeded livestock-use standards: pH (20 percent above upper limit) and TDS (20 percent).

7.2.5.2.2 Muddy Sandstone aquifer

The chemical composition of groundwater in the Muddy Sandstone aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were fresh (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 688 to 1,570 mg/L, with a median of 1,100 mg/L.

The chemical composition of groundwater in the Muddy Sandstone aquifer in the BHB also was characterized and the quality evaluated on the basis of 23 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram C). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny, and indicated that most of the water was slightly saline (48 percent) (Appendix F2; Appendix H2, diagram C; supplementary data tables). TDS concentrations ranged from 1,040 to 47,300 mg/L, with a median of 4,810 mg/L.

Concentrations of some properties and constituents in water from the Muddy Sandstone aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and SMCLs): fluoride (20 percent of the samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), pH (80 percent above upper limit), sulfate (60 percent), and fluoride (40 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), sulfate (59 percent), chloride (57 percent), and pH (5 percent below lower limit and 10 percent above upper limit). TDS concentrations in 9 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were SAR (80 percent), sulfate (60 percent), boron (25 percent), chloride (20 percent), and pH (20 percent above upper limit). One property had values greater than livestock-use standards: pH (80 percent above upper limit).

The produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: filtered iron (100 percent), TDS (78 percent), chloride (74 percent), sulfate (64 percent), and pH (5 percent below lower limit). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (48 percent), chloride (22 percent), sulfate (14 percent), and pH (5 percent below lower limit and 10 percent above upper limit).

7.2.5.2.3 Thermopolis confining unit

The chemical composition of groundwater in the Thermopolis confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (60 percent of samples) and the remaining waters were slightly or very saline (supplementary data tables). TDS concentrations ranged from 218 to 25,100 mg/L, with a median of 638 mg/L.

Concentrations of some properties and constituents in water from the Thermopolis confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents frequently exceeded health-based standards (USEPA MCLs and HALs): cadmium (100 percent of samples analyzed for the constituent) and selenium (50 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (80 percent), manganese (67 percent), sulfate (40 percent), filtered iron (33 percent), pH (25 percent below lower limit), and fluoride (20 percent). TDS concentrations in 20 percent of environmental water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in the environmental water samples that had concentrations greater than agricultural-use standards were cadmium (100 percent), cobalt (100 percent), sulfate (80 percent), manganese (67 percent), selenium (50 percent), SAR (40 percent), pH (25 percent below lower limit), chloride (20 percent), and TDS (20 percent). Several properties and constituents were measured at concentrations greater than livestock-use standards: cadmium (100 percent), selenium (50 percent), pH (25 percent below lower limit), sulfate (20 percent), and TDS (20 percent).

7.2.5.3 Cloverly aquifer

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

Physical characteristics

The Lower Cretaceous-age Cloverly Formation comprises the Cloverly aquifer **(Plate III)**. The Cloverly Formation consists of three distinctive units in the BHB – an upper sandstone interbedded with silty sandstone and shale, known as the "Dakota Sandstone"; a middle shale unit with sparse sandstone lenses; and a lower lenticular sandstone with conglomeratic sandstone and some siltstone and shale, known as the "Lakota Sandstone" (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b, 1986; Plafcan et al., 1993). The reported thickness of the Cloverly Formation, including all three lithologic units, ranges from about 85 ft in the southeastern part of the Bighorn Basin to about 470 ft in the northwestern part (Libra et al., 1981, Table IV-1). The aquifer is confined above by the Mowry–Thermopolis confining unit and below by the Morrison confining unit **(Plate III)**. Hydrogeologic information describing the Cloverly aquifer, including well-yield and spring-discharge measurements and other hydraulic properties, is summarized on **Plate IX**.

The Cloverly aquifer was examined as a potential source of public supply in the northeastern BHB (Western Water Consultants, Inc., 1982a,b). Western Water Consultants reported that both sandstone units were permeable and ranged in thickness from 70 to 90 ft. The investigators speculated that the middle shale unit may function as a leaky confining unit between the two sandstone units. The sandstone units were reported to be confined where buried but unconfined in outcrop areas. Permeability was reported to be intergranular and to be fracture enhanced in anticlines.

Chemical characteristics

The chemical composition of groundwater in the Cloverly aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2,** diagram H). TDS concentrations were variable and indicated that most waters were slightly saline (80 percent of samples) and the remaining waters were fresh or moderately saline (**Appendix E2; Appendix G2**, diagram H; supplementary data tables). TDS concentrations ranged from 814 to 3,080 mg/L, with a median of 2,350 mg/L.

The chemical composition of groundwater in the Cloverly aquifer in the BHB also was characterized and the quality evaluated on the basis of 27 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram D).TDS concentrations from produced waters were variable and indicated that most waters were moderately saline (56 percent of samples) and the remaining waters were slightly or very saline **(Appendix F2; Appendix H2**, diagram D; supplementary data tables). TDS concentrations ranged from 1,320 to 11,500 mg/L, with a median of 4,290 mg/L.
Concentrations of some properties and constituents in water from the Cloverly aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): boron (29 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), filtered iron (50 percent), manganese (50 percent), boron (29 percent), pH (17 percent above upper limit), and fluoride (10 percent).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (70 percent), sulfate (64 percent), and pH (4 percent below lower limit and 8 percent above upper limit). TDS concentrations in 7 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were sulfate (100 percent), SAR (60 percent), TDS (60 percent), and mercury (50 percent). Values of one property (pH) exceeded livestock-use standards (17 percent above upper limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (93 percent), TDS (93 percent), and sulfate (64 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (33 percent), pH (4 percent below lower limit and 8 percent above upper limit), chloride (7 percent), and sulfate (4 percent).

7.2.5.4 Morrison confining unit and aquifer

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

Physical characteristics

The Upper Jurassic-age Morrison Formation comprises the Morrison confining unit and aquifer in the BHB. The Morrison confining unit and aquifer consists primarily of interbedded variegated shale and mudstone, with lesser silty fine-grained sandstone, limestone, and lenses of conglomerate (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The fine-grained lithologies (for example, shale and mudstone) are considered confining units, whereas the interbedded sandstone beds are considered local aquifers or subaquifers (Libra et al., 1981; Plafcan et al., 1993). The Morrison Formation is defined herein as a confining unit and aquifer **(Plate III)**. The reported thickness of the Morrison confining unit and aquifer in the BHB ranges from 75 ft in the northwest to 300 ft in the southeast (Libra et al., 1981, table IV-1). The Morrison Formation is overlain by the Cloverly Formation and underlain by the Sundance Formation **(Plate III)**. Confined conditions likely predominate in the Morrison confining unit and aquifer except in outcrop areas. Sandstone beds within the Morrison confining unit and aquifer are considered to have limited potential for development because of small outcrop area and small yields adequate only for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Little hydrogeologic information is available describing the Morrison confining unit, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Morrison confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations (604 and 4,780 mg/L) indicated that waters were fresh and moderately saline (Appendix E2; supplementary data tables).

The chemical composition of groundwater in the Morrison confining unit and aquifer in the BHB also was characterized and the quality evaluated on the basis of 10 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,270 to 18,700 mg/L, with a median of 7,130 mg/L.

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

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed for in produced-water samples had available health-based standards (USEPA MCLs and HALs) for comparison. The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (70 percent), sulfate (50 percent), and pH (20 percent above upper limit). TDS concentrations in 40 percent of produced-water samples exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (50 percent), SAR (50 percent), and TDS (50 percent). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

The produced-water samples had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (100 percent), chloride (80 percent), and sulfate (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: chloride (60 percent), TDS (60 percent), and pH (20 percent above upper limit).

7.2.5.5 Sundance confining unit and aquifer

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

Physical characteristics

The Middle and Upper Jurassic-age Sundance Formation comprises the Sundance confining unit and aquifer in the BHB **(Plate III)**. The Sundance aquifer consists primarily of greenish-gray shale interbedded with glauconitic sandstone, siltstone, and limestone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Low permeability fine-grained lithologies (for example, shale, siltstone) are considered confining units, whereas the interbedded sandstone beds are considered local aquifers or subaquifers (Libra et al., 1981; Plafcan et al., 1993). The Sundance Formation is defined herein as a confining unit and aquifer **(Plate III)**. The reported thickness of the hydrogeologic unit in the BHB ranges from 200 to 370 ft (Lowry et al., 1976; Libra et al., 1981, Table IV-1; Western Water Consultants, Inc., 1982a,b, 1986). The Sundance Formation is overlain by the Morrison Formation and underlain by the Gypsum Spring Formation **(Plate III)**. Confined conditions likely predominate except in outcrop areas, where unconfined (water-table) conditions are likely. Sandstone beds within the aquifer are considered to have limited potential for development because of small extent and small yields only adequate for stock or domestic use (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1986; Plafcan et al., 1993). Little hydrogeologic information is available describing the Sundance confining unit and aquifer, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Sundance confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of one environmental water sample from one well. Individual constituent concentrations are listed in **Appendix E2.** The TDS concentration (708 mg/L) indicated that the water was fresh (Appendix E2; supplementary data tables).

The chemical composition of groundwater in the Sundance confining unit and aquifer in the BHB also was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** TDS concentrations from produced waters were variable and ranged from slightly to very saline (**Appendix F2**; supplementary data tables). TDS concentrations ranged from 2,280 to 14,300 mg/L, with a median of 3,080 mg/L.

Concentrations of some properties and constituents in the Sundance confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations in one environmental water sample with health-based standards (USEPA MCLs and HALs), the environmental water was suitable for domestic use. One property (TDS) and one constituent (sulfate) exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Most water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed in produced-water samples had available health-based standards (USEPA MCLs and HALs) for comparison. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: chloride (100 percent of samples analyzed for the constituent), TDS (100 percent), sulfate (67 percent), and pH (11 percent above upper limit). TDS concentrations in 22 percent of produced-water samples from the Sundance aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agriculture and livestock use in the BHB. Sulfate was measured in the environmental water sample at a concentration greater than the agricultural-use standard. No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: chloride (100 percent), TDS (100 percent), and sulfate (67 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: sulfate (22 percent), TDS (22 percent), and pH (11 percent above upper limit).

7.2.5.6 Gypsum Spring confining unit and aquifer

The physical and chemical characteristics of the Gypsum Spring confining unit and aquifer in the BHB are described in this section of the report.

Physical characteristics

The Middle Jurassic-age Gypsum Spring Formation comprises the Gypsum Spring confining unit and aquifer in the BHB. The Gypsum Spring confining unit and aquifer consists primarily of reddish-brown siltstone, claystone, and shale, with thin limestone and massive gypsum beds (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Low-permeability fine-grained lithologies (for example, shale, siltstone) are considered confining units, whereas solution zones in gypsum beds are considered local aquifers or subaquifers, although with very poor groundwater quality (Libra et al., 1981; Plafcan et al., 1993). The Gypsum Spring Formation is defined as a confining unit and aquifer **(Plate III)**. The reported thickness of the Gypsum Spring Formation in the BHB ranges from 200 to 370 ft (Lowry et al., 1976; Libra et al., 1981, table IV-1; Western Water Consultants, Inc., 1982a,b, 1986). The Gypsum Spring Formation is overlain by the Sundance Formation and is underlain by the Nugget Sandstone or Chugwater Group, depending on the presence or absence of the Nugget Sandstone **(Plate III)**. Confined conditions likely predominate in the Gypsum Spring confining unit and aquifer except in outcrop areas, where unconfined (water-table) conditions are likely.

Very few wells are completed in the Gypsum Spring confining unit and aquifer, and potential for development for any use is very limited because of small outcrop extent, probable poor water quality, and availability of better groundwater sources (Dana, 1962b; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1986; Plafcan et al., 1993). Very little hydrogeologic information is available describing the Gypsum Spring confining unit and aquifer, but well-yield and spring-discharge measurements and other hydraulic properties are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Gypsum Spring confining unit and aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were slightly saline (75 percent of samples analyzed for the property) and the remaining waters were fresh (Appendix E2; supplementary data tables). TDS concentrations ranged from 342 to 2,650 mg/L, with a median of 1,830 mg/L.

Concentrations of some properties and constituents in water from the Gypsum Spring confining unit and aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (75 percent) and TDS (75 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. One constituent and one property in environmental water samples had concentrations greater than agricultural-use standards: sulfate (75 percent) and TDS (50 percent). No properties or constituents exceeded State of Wyoming livestock standards.

7.2.5.7 Nugget aquifer

No information was located to describe the physical and chemical characteristics of the Nugget aquifer in the BHB; however, this aquifer is described in the WRB section of this report.

7.2.5.8 Recharge, discharge, and groundwater movement

Recharge to lower and middle Mesozoic aquifers and confining units in the BHB is primarily by infiltration of precipitation and streamflow in outcrop areas (Berry and Littleton, 1961; Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b). Infiltration of water from overlying saturated Quaternary unconsolidated deposits and interformational flow in fracture zones along anticlines also may contribute to recharge locally (Berry and Littleton, 1961; Lowry et al., 1976; Plafcan et al., 1993).

Discharge from lower and middle Mesozoic aquifers and confining units is both natural and anthropogenic. Groundwater discharges from lower and middle Mesozoic aquifers and confining units through seeps, springs, interformational movement, and gaining streams (Lowry et al., 1976; Libra et al., 1981). The primary anthropogenic sources of discharge from aquifers in the lower and middle Mesozoic aquifers and confining units likely are oilfield wells.

Potentiometric-surface maps have not been constructed for any of the lower and middle Mesozoic aquifers and confining units. Groundwater movement in these hydrogeologic units is assumed to be from outcrop areas (assumed to represent recharge areas) to the basin interior (Berry and Littleton, 1961; Lowry et al., 1976; Libra et al., 1981).

7.2.6 Chugwater–Dinwoody aquifer and confining unit

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

Physical characteristics

The Chugwater aquifer is composed of the Lower and Upper Triassic-age Chugwater Group or Formation. The Dinwoody confining unit is composed of the Lower Triassic-age Dinwoody Formation. The Chugwater–Dinwoody aquifer and confining unit confines and separates the underlying Paleozoic aquifer system from the overlying lower and middle Mesozoic aquifers and confining units **(Plate III)**. The reported thickness of the Chugwater–Dinwoody aquifer and confining unit ranges from about 450 to 1,200 ft (Libra et al., 1981, table IV-1; Western Water Consultants, Inc., 1983b; Jarvis, 1986a). The Chugwater Group or Formation is composed of distinctive red beds and includes fine-grained sandstone, siltstone, and shale with some thin lenticular beds of limestone and gypsum (Darton, 1906a,b; Condit, 1917; Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Dinwoody Formation includes silty shale and siltstone, with limestone, dolomite, and gypsum in the upper part (Lowry et al., 1976; Libra et al., 1981). Although the Chugwater Group or Formation and the Dinwoody Formation are confining units for the underlying Paleozoic aquifer system, both formations may yield small quantities of water to wells and springs from interbedded limestones, gypsum beds, and sandstones at some locations in the BHB (Libra et al., 1981; Western Water Consultants, Inc., 1983b; Jarvis, 1986). Little hydrogeologic information is available describing the Chugwater-Dinwoody aquifer and confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for both hydrogeologic units composing the confining unit are summarized on **Plate IX**.

Chemical characteristics

Groundwater-quality data are presented and described for both the Chugwater aquifer and Dinwoody confining unit composing the Chugwater–Dinwoody aquifer and confining unit in this section of the report.

7.2.6.1 Chugwater aquifer

The chemical composition of groundwater in the Chugwater aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from seven wells and six springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram I). TDS concentrations were variable and indicated that most waters were slightly saline (77 percent of samples) and the remaining waters were fresh (**Appendix E2; Appendix G2**, diagram I; supplementary data tables). TDS concentrations ranged from 251 to 2,840 mg/L, with a median of 1,960 mg/L.

The chemical composition of groundwater in the Chugwater aquifer also was characterized and the quality evaluated on the basis of 99 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram E). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny; however, the concentrations indicated that most of the waters were very saline (43 percent) (**Appendix F2; Appendix H2**, diagram E; supplementary data tables). TDS concentrations ranged from 1,170 to 57,500 mg/L, with a median of 24,100 mg/L.

Concentrations of some properties and constituents in the Chugwater aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent infrequently exceeded health-based standards (USEPA MCLs and HALs): nitrate plus nitrite (8 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (92 percent), sulfate (85 percent), and pH (8 percent below lower limit).

Most available water-quality analyses for the Chugwater aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), filtered iron (100 percent), sulfate (98 percent), chloride (90 percent), and pH (6 percent above upper limit). TDS concentrations in 68 percent of produced-water samples from the Chugwater aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents in water from the Chugwater aquifer exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (92 percent), TDS (46 percent), and selenium (33 percent). Values of one property (pH) were greater than livestock-use standards (8 percent below lower limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (98 percent), TDS (95 percent), and chloride (92 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (83 percent), sulfate (70 percent), chloride (69 percent), and pH (6 percent above upper limit).

7.2.6.2 Dinwoody confining unit

The chemical composition of groundwater in the Dinwoody confining unit in the BHB was characterized and the quality evaluated on the basis of one produced-water sample from a well. Individual constituent concentrations for this sample are listed in **Appendix F2**. The TDS concentration (8,590 mg/L) indicated that the water was moderately saline.

Concentrations of some properties and constituents in water from the Dinwoody confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample with few chemical analyses of properties and constituents; thus, comparisons between concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had available health-based standards (USEPA MCLs and HALs), so no comparisons could be made. The produced-water sample had concentrations of one property (TDS) and two constituents (chloride and sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the BHB. The produced-water sample had concentrations of two constituents (chloride and sulfate) that exceeded agricultural-use standards. The produced-water sample had concentrations of one property (TDS) and one constituent (chloride) that exceeded livestock-use standards.

7.2.7 Paleozoic aquifer system

The Paleozoic aquifer system in the BHB includes lithostratigraphic units ranging in age from lower Ordovician to Permian or Lower Triassic(?). The upper boundary of the aquifer system is unclear and subject to different interpretations by different investigators **(Plate III)**. The differences are attributable to contradictory hydrogeologic classification of the intertonguing facies of the Permian and Lower Triassic-age Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation), and to different interpretations of the amount of hydraulic connection between these formations and the underlying Tensleep aquifer, described in detail under "Goose Egg–Phosphoria aquifer and confining unit" in the Wind River Basin, **Section 7.1.12** of this report. The Paleozoic aquifer system defined herein comprises four hydrogeologic units – the Goose Egg–Phosphoria aquifer and confining unit, Tensleep aquifer, Amsden confining unit, and Madison–Bighorn aquifer **(Plate III)**. The Paleozoic aquifer system is defined herein as being confined above by overlying low-permeability shales and siltstones of the Chugwater–Dinwoody confining unit and below by thick, low-permeability shales of the Gallatin–Gros Ventre confining unit **(Plate III)**.

The Tensleep and Madison–Bighorn aquifers are the most developed aquifers in the Paleozoic aquifer system. Both aquifers are considered "major" or "principal" aquifers because some wells at some locations can yield hundreds to thousands of gallons per minute. Consequently, the aquifers have been developed for domestic, public-supply, irrigation, or stock use in the BHB. Both aquifers also are extensively utilized for petroleum production, typically in the numerous anticlines rimming the basins proper.

The groundwater quality of aquifers contained in the Paleozoic aquifer system varies greatly throughout the BHB. Recharge to these units generally occurs where the formations crop out near basin margins. Near recharge areas, water in these aquifers may be relatively fresh and suitable for most uses. This is where most domestic, public-supply, irrigation, or stock wells are completed. Elsewhere, and with increasing depth (as indicated primarily by produced-water samples) and as the water moves away from outcrop into the basin interior, the water may have high TDS concentrations (be highly mineralized) and not suitable for most uses or only marginally suitable for livestock and other uses. Only oil or gas wells are completed in deeply buried Paleozoic hydrogeologic units.

7.2.7.1 Goose Egg–Phosphoria aquifer and confining unit

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

Physical characteristics

The Goose Egg–Phosphoria aquifer and confining unit hydrogeologic unit comprises the Permian and Lower Triassic-age Goose Egg Formation and the Permian-age Phosphoria and Park City Formations **(Plate III)**. The Goose Egg Formation is an evaporite sequence consisting of gypsiferous siltstone, mudstone, and silty shale; its thickness ranges from 100 to 300 ft (Sheldon, 1963). Sheldon noted intertonguing between the Park City and Goose Egg Formations. Sheldon considered the Park City Formation representative of a western facies and the Goose Egg Formation representative of an eastern facies, their boundary located at the longitude of Worland in Washakie County. The Phosphoria Formation is considered equivalent to the Goose Egg Formation (Cooley, 1986a; Plafcan et al., 1993). The Park City Formation is a cherty dolomitic carbonate sequence with a thickness ranging from 25 to 325 ft (Sheldon, 1963). Overall, the formations have generally low permeability, except where lithology is favorable or faults and fractures are present (Stone, 1967). With the exception of oil wells, relatively few wells are installed in the Goose Egg–Phosphoria aquifer and confining unit, and development is limited to low-yield wells located along the basin margin where the formations crop out and drilling depths are relatively shallow. Most information describing the formations composing the hydrogeologic unit is from oil field data.

The complex intertonguing and interfingering relation between carbonate facies, siltstone facies, and shale and evaporate facies in the Goose Egg–Phosphoria aquifer and confining unit creates numerous small permeable zones that can function as individual aquifers (or subaquifers) or provide hydraulic connection with the underlying Tensleep aquifer (Libra et al., 1981; Cooley, 1986a; Jarvis, 1986; Spencer, 1986a). Consequently, the Goose Egg–Phosphoria aquifer and confining unit can be considered a sequence of rocks that function as both aquifer (some carbonate and evaporite sequences) and confining or leaky confining unit (siltstone, evaporite, and shale sequences), and that definition is used herein **(Plate III)**. Nonetheless, some investigators believe that there is enough hydraulic connection with the underlying Tensleep aquifer that the three formations (or parts of the three formations) can be considered part of the Tensleep aquifer, at least in parts of the BHB **(Plate III)**. The different interpretations of the hydraulic function of the three formations can be seen in the numerous and commonly different hydrogeologic unit classifications **(Plate III)**. Recharge to these units is likely from infiltration of precipitation and streamflow in outcrop areas, interformational flow in fractures along anticlines, and possibly by infiltration of water from overlying saturated alluvium (Berry and Littleton, 1961; Lowry et al., 1976). Discharge from these units is likely to seeps, springs, streams, and interformational movement

(Berry and Littleton, 1961; Lowry et al., 1976). Well-yield and spring-discharge measurements and other hydraulic properties for the hydrogeologic unit are summarized on **Plate IX**; most of these data are from wells or drill-stem tests associated with petroleum extraction from the Phosphoria Formation.

Chemical characteristics

Groundwater-quality data are presented and described for the Goose Egg aquifer and confining unit and the Phosphoria aquifer and confining unit.

7.2.7.1.1 Goose Egg aquifer and confining unit

The chemical composition of groundwater in water from the Goose Egg aquifer and confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 10 wells and two springs. Individual constituent concentrations are listed in Appendix E2. TDS concentrations were variable and indicated that most waters were fresh (83 percent of samples) and the remaining waters were slightly saline (Appendix E2; Appendix G2, diagram J; supplementary data tables). TDS concentrations ranged from 205 to 2,690 mg/L, with a median of 397 mg/L.

Concentrations of some properties and constituents in water from the Goose Egg aquifer and confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded a health-based standard (USEPA MCLs and HALs): boron (100 percent of samples analyzed for the constituent). Concentrations of one property and two constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (33 percent), TDS (33 percent), and fluoride (8 percent).

Concentrations of some properties and constituents in water from the Goose Egg aquifer and confining unit exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Two constituents and one property in environmental water samples had concentrations greater than agricultural-use standards: boron (100 percent), sulfate (33 percent), and TDS (17 percent). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

7.2.7.1.2 Phosphoria aquifer and confining unit

The chemical composition of groundwater in the Phosphoria aquifer and confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from five wells. Summary statistics calculated for available constituents are listed in Appendix E2. TDS concentrations were highly variable and indicated that some waters were slightly saline (40 percent of samples) and the remaining waters were fresh to briny (Appendix E2; supplementary data tables). TDS concentrations ranged from 787 to 49,400 mg/L, with a median of 2,840 mg/L.

The chemical composition of groundwater in the Phosphoria aquifer and confining unit also was characterized and the quality evaluated on the basis of 505 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram F). TDS concentrations from produced-water samples were highly variable and ranged from slightly saline to briny; however, the concentrations indicated that most of the waters were moderately saline (59 percent) (**Appendix F2; Appendix H2**, diagram F; supplementary data tables). TDS concentrations ranged from 1,080 to 220,000 mg/L, with a median of 7,200 mg/L.

Concentrations of some properties and constituents in water from the Phosphoria aquifer and confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of two constituents exceeded health-based standards (USEPA MCLs and HALs): boron (67 percent of samples analyzed for the constituent) and fluoride (33 percent). Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), filtered iron (100 percent), fluoride (67 percent), chloride (60 percent), and pH (33 percent below lower limit). TDS concentrations in 20 percent of environmental water samples from the Phosphoria aquifer and confining unit exceeded State of Wyoming Class IV standards.

Most water-quality analyses available for the Phosphoria aquifer and confining unit were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of two constituents that exceeded health-based standards (USEPA MCLs and HALs): strontium (100 percent of samples analyzed for the constituent) and barium (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (98 percent), chloride (79 percent), filtered iron (75 percent), and pH (3 percent below lower limit and 6 percent above upper limit). TDS concentrations in 31 percent of produced-water samples from the Phosphoria aquifer and confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (100 percent), TDS (80 percent), boron (67 percent), chloride (60 percent), and SAR (25 percent). The properties and constituents that had concentrations greater than livestock-use standards were pH (33 percent below lower limit), boron (33 percent), chloride (20 percent), and TDS (20 percent).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (98 percent), TDS (97 percent), chloride (91 percent), filtered iron (25 percent), lithium (8 percent), and pH (less than 1 percent above upper limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (73 percent), sulfate (50 percent), chloride (23 percent), and pH (3 percent below lower limit and 6 percent above upper limit).

7.2.7.2 Tensleep aquifer

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

Physical characteristics

The Tensleep aquifer is a major aquifer in the BHB. The aquifer is used primarily as a source of water for domestic, stock, and (rarely) irrigation purposes along the eastern margin of the BHB, where the hydrogeologic units composing the aquifer are exposed at land surface (crop out) or are at shallow depths (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). Large volumes of water also are withdrawn from the numerous oilfields developed, mostly on anticlines, throughout the basin (Western Water Consultants, Inc., 1982a,b; Cooley, 1986a; Doremus, 1986).

Most wells flow at land surface under artesian pressure, except near some outcrops associated with anticlines, where unconfined conditions exist (Horn, 1963; Cooley, 1984, 1986a; Hinckley et al., 1982a). Flowing wells located along the BHB margin may yield large and dependable supplies of potable water, especially those located near anticlines, but reported well and spring yields vary considerably **(Plate IX)**. Water in the aquifer generally is under artesian pressure, with wellhead pressures generally less than 50 pounds per square inch (psi) in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported the same wellhead pressures as Cooley did in outcrop areas and wellhead pressures ranging from 200 to 5,000 psi in the basin interior.

The Tensleep aquifer comprises the Pennsylvanian-age Tensleep Sandstone and Ranchester Limestone Member of the Amsden Formation (Cooley, 1984, 1986a; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Some investigators also include the overlying Permian and Lower Triassic-age Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) as part of the aquifer, but note that hydraulic connection between the hydrogeologic units is dependent on the absence of local confining units (low permeability lithologies) and on the extent of fracture-enhanced permeability associated with folds and faults (Western Water Consultants, Inc., 1982a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Thus, the upper boundary (and associated upper confining unit) of the aquifer is subject to different interpretations among the various investigators. The Tensleep aquifer is defined herein as being confined above by overlying low-permeability shales and siltstones of the overlying Goose Egg-Phosphoria aquifer and confining unit hydrogeologic unit **(Plate III)**; however, the overlying Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) may be in hydraulic connection with (and considered part of) the aquifer at some locations where folding and faulting and associated fracturing allows for hydraulic connection of these units (Western Water Consultants, Inc., 1982a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). The aquifer is confined below by shales of the underlying Horseshoe Shale Member of the Amsden Formation (Cooley, 1984, 1986a; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. The Horseshoe Shale Member corresponds to the Amsden aquifer, as described in a following section.

The Tensleep Sandstone is composed of predominantly tan, cross-bedded, well-sorted, fine- to medium-grained sandstone cemented with carbonate and silica (Todd, 1963; Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Love at al., 1993; Plafcan et al., 1993). Cherty dolomite in the upper part and discontinuous marine limestone and dolomite (carbonates) in the lower part of the formation were reported by Moore (1984). Porosity and permeability in the Tensleep Sandstone are primarily intergranular, and decrease with secondary cementation and recrystallization, both of which increase with burial depth (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966). Fractures and solution processes (in carbonate-rich zones) may enhance intergranular sandstone permeability (Stone, 1967; Lowry et al., 1976). Interstitial porosity decreases from the eastern basin margin to the basin interior (and with increasing depth) due to precipitation of dolomite and silica (Todd, 1963; Bredehoeft, 1964; Lawson and Smith, 1966; Fox et al., 1975). Secondary fracture porosity and permeability are common in folds and faults in the BHB, and these locations have the best potential for groundwater development (Western Water Consultants, Inc., 1982a,b; Jarvis, 1986; Spencer, 1986a).

The Ranchester Limestone Member of the Amsden Formation is composed primarily of limestone. The geologic unit is not permeable everywhere; Jarvis (1986a, p. 37) noted that the

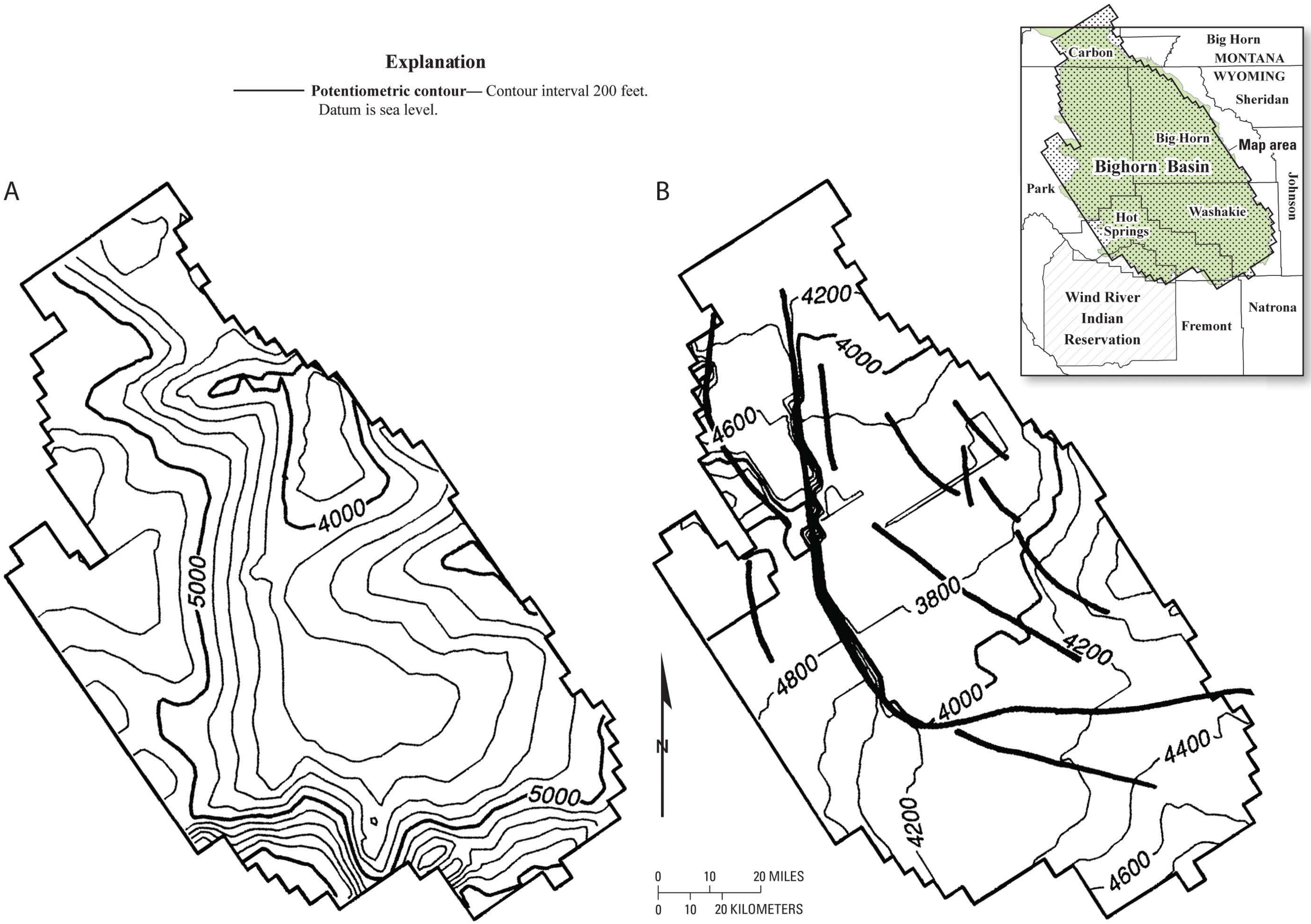


Figure 7-10. Comparison of predevelopment potentiometric surfaces, Tensleep aquifer, Bighorn Basin, Wyoming (modified from Bredehoeft et al., 1992, Figures 7 and 8). A, Bredehoeft and Bennett's (1971) predevelopment potentiometric map for the Tensleep aquifer. B, Haun's (1988) predevelopment potentiometric map for the Tensleep aquifer. Heavy lines indicate major faults.

unit is "probably impermeable except where limestones have been dolomitized."

Numerous potentiometric surfaces of the Tensleep aquifer in the BHB have been constructed because of its importance as a petroleum reservoir and its utility as a model of artesian basins in the Wyoming foreland. Predevelopment potentiometric surfaces of the aquifer have been constructed by Todd (1963), Bredehoeft and Bennett (1972), and Haun (1984). These investigators based their potentiometric surfaces exclusively on hydraulic-head data from the Tensleep Sandstone and did not include hydraulic-head data from the underlying Ranchester Limestone Member of the Amsden Formation or the overlying Phosphoria and (or) Goose Egg Formations and equivalents (Park City Formation) (as described above, these last geologic units are considered part of the aquifer by several investigators). The potentiometric surface constructed by Bredehoeft and Bennett (1972) has been widely reproduced and discussed since publication (and is reproduced herein on **Plate XII**). The potentiometric surfaces of Todd (1963) and Bredehoeft and Bennett (1972) are fairly similar, and both neglect the effects of faulting; both maps show groundwater flowing uniformly from outcrops along the basin margins (recharge areas) to the deep, central parts of the basin. The potentiometric-surface map constructed by Haun (1984) differs from that of Bredehoeft and Bennett (1972). In addition to hydraulic head, Haun utilized oilfield tilts from Zapp (1956) and, more importantly, included faults as barriers to lateral groundwater flow. Consequently, the interpretations of the predevelopment potentiometric surfaces of the Tensleep aquifer **(Figure 7-10)** are substantially different (Bredehoeft et al., 1992). Bredehoeft et al. (1992, p. 535) noted that Haun (1984) minimized higher outcrop elevations as control, and also noted that hydraulic potentials were several hundred feet lower than those of Bredehoeft and Bennett's (1972) potentiometric surface. By examining the various hydraulic factors that affect construction of potentiometric surfaces, Bredehoeft et al. (1992) concluded that major faults can act as both barriers and vertical conduits for regional flow, and that major fault zones control regional Paleozoic aquifer groundwater flow in the BHB. This led them to conclude that the hydraulic heads presented in both Tensleep aquifer predevelopment potentiometric surface maps are likely "too low over much of the basin" (Bredehoeft et al., 1992, p. 545).

The potentiometric surface of the Tensleep aquifer in the northeastern BHB was mapped by Western Water Consultants, Inc. (1982a, Plate 4; 1982b, Plate 4; 1983c, Plate 4). These maps were based on hydraulic-head data from the Tensleep Sandstone and overlying Phosphoria Formation. (The Phosphoria Formation and equivalent Park City Formation are considered part of the Tensleep aquifer by several investigators.) The general direction of groundwater flow is from outcrop areas along the eastern basin margin toward the basin interior. Large cones of depression were associated with the Byron, Garland, Sage Creek, Deaver, and Frannie oilfields (Western Water Consultants, Inc., 1982a,b). Drawdown at the Manderson and Bonanza oilfields was hypothesized (Western Water Consultants, Inc., 1983c). Discontinuity of the potentiometric surface near the Manderson anticline was noted and attributed to a fault acting as a partial barrier to groundwater flow (Western Water Consultants, Inc., 1983c).

Detailed mapping of the potentiometric surface of the Tensleep aquifer was conducted in the southeastern BHB by Jarvis (1986, Plate 4) and southwestern BHB by Spencer (1986a, Plate 4). Cooley (1986a) mapped the potentiometric surface of the aquifer in the Tensleep area [a small part of the same area mapped by Jarvis (1986a)]. The potentiometric-surface maps of Jarvis (1986, Plate 4) and Spencer (1986a, Plate 4) were meant to complement one another, and both maps have been combined into a single potentiometric-surface map for this study on **Plate XIII**. The investigators accounted for the many effects of folding and faulting on interpretation of the potentiometric surface, incorporating and expanding upon the improved understanding of hydraulic interconnection between recharge areas along Wyoming structural basin margins and deep central basins provided by Huntoon (1985a). The potentiometric-surface maps of the Tensleep aquifer constructed by Jarvis and Spencer are the most detailed available for any aquifer in the BHB, and the effects of these numerous structures on the potentiometric surface of the Tensleep aquifer can be seen on **Plate XIII**.

Chemical Characteristics

Groundwater-quality data are presented and described for only one lithostratigraphic unit (Tensleep Sandstone) included in the Tensleep aquifer. Groundwater-quality data for the underlying Ranchester Limestone Member of the Amsden Formation are included in the description of the Amsden aquifer because groundwater samples from the Amsden aquifer generally were only associated with the Amsden Formation, not the three members composing it.

The chemical composition of groundwater in the Tensleep aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 38 wells and six springs. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix G2, diagram K). Summary statistics calculated for available constituents are listed in Appendix E2. TDS concentrations were variable and indicated that most waters were fresh (82 percent of samples) and the remaining waters were slightly to moderately saline (Appendix E2; Appendix G2, diagram K; supplementary data tables). TDS concentrations ranged from 156 to 3,750 mg/L, with a median of 259 mg/L.

Concentrations of some properties and constituents in water from the Tensleep aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent infrequently exceeded health-based standards (USEPA MCLs and HALs): fluoride (2 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (100 percent exceeded lower limit), TDS (27 percent), sulfate (23 percent), filtered iron (21 percent), fluoride (15 percent), pH (3 percent below lower limit), and chloride (2 percent).

The chemical composition of groundwater in the Tensleep aquifer also was characterized and the quality evaluated on the basis of 504 produced-water samples from wells. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram G). Summary statistics calculated for available constituents are listed in Appendix F2. TDS concentrations from produced-water samples were highly variable and ranged from fresh to very saline; however, the concentrations indicated that most of the waters were moderately saline (61 percent) (Appendix F2; Appendix H2, diagram G; supplementary data tables). TDS concentrations ranged from 324 to 33,700 mg/L, with a median of 3,650 mg/L.

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one constituent that exceeded health-based standards (USEPA MCLs and HALs): strontium (50 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (100 percent), manganese (100 percent), TDS (99 percent), sulfate (96 percent), chloride (38 percent), and pH (1 percent below lower limit and 4 percent above upper limit). TDS concentrations in 6 percent of produced-water samples from the Tensleep aquifer exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (26 percent), TDS (14 percent), chloride (7 percent), boron (5 percent), and filtered iron (5 percent). One property (pH) had values greater than a livestock-use standard (3 percent below lower limit).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (97 percent), TDS (89 percent), chloride (60 percent), filtered iron (50 percent), and pH (less than 1 percent below lower limit). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (28 percent), sulfate (21 percent), pH (1 percent below lower limit and 4 percent above upper limit), and chloride (2 percent).

Jarvis (1986) noted two types of water in the Tensleep aquifer. Calcium-bicarbonate-type waters were predominant near the basin margin, whereas calcium-sulfate-type waters were predominant in the basin interior. Jarvis also attributed large concentrations of sodium, calcium, sulfate, and chloride in water from the Tensleep aquifer to anhydrite dissolution. Evaluation of a much larger number of groundwater samples compiled for this study indicates that ionic composition (water type) clearly changes with increasing TDS concentration (Appendix G2, diagram K; Appendix H2, diagram G). Groundwaters from the Tensleep aquifer classified as fresh or slightly saline generally were calcium-bicarbonate and calcium-magnesium-bicarbonate type, whereas waters classified as moderately to very saline generally were classified as (and evolve toward) sodium-sulfate type.

7.2.7.3 Amsden confining unit

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

Physical characteristics

The Amsden confining unit in the Bighorn Basin is composed of the Horseshoe Shale Member of the Middle and Lower Pennsylvanian and Upper Mississippian-age Amsden Formation (Jarvis, 1986; Spencer, 1986a). The Horseshoe Shale Member confines and separates the underlying Madison–Bighorn aquifer from the overlying Tensleep aquifer **(Plate III)**. The reported thickness of the entire Amsden Formation, including all three members, ranges from about 120 to 300 ft in the BHB (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Most hydrogeologic data for the Amsden confining unit are assigned to the Amsden Formation, not individual members; consequently, well-yield and spring-discharge measurements and other hydraulic properties for the entire formation are summarized on **Plate IX**, even though some measurements may be from the Ranchester Limestone and Darwin Sandstone Members, which are included in the Tensleep and Madison aquifers, respectively **(Plate III)**.

Chemical characteristics

Groundwater-quality samples from the Amsden confining unit are described in this section. Groundwater-quality data for the Amsden confining unit are assigned to the Amsden Formation, not individual members; consequently, groundwater-quality for the entire formation are summarized, even though some measurements may be from the Ranchester Limestone and Darwin Sandstone Members. The chemical composition of groundwater in the Amsden confining unit in the BHB was characterized and the quality evaluated on the basis of 21 produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F2. Major-ion composition in relation to TDS is shown on a trilinear diagram (Appendix H2, diagram H). TDS concentrations from produced-water samples were highly variable and ranged from fresh to briny; however, concentrations indicated most of the waters were moderately saline (52 percent) (Appendix F2; Appendix H2; supplementary data tables). TDS concentrations ranged from 590 to 53,500 mg/L, with a median of 3,280 mg/L.

Concentrations of some properties and constituents in water from the Amsden confining unit in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one constituent that exceeded health-based standards (USEPA MCLs and HALs): strontium (50 percent of samples analyzed for the constituent). The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), sulfate (95 percent), chloride (52 percent), and pH (15 percent above upper limit). TDS concentrations in 10 percent of produced-water samples from the Amsden confining unit exceeded State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. The produced-water samples generally had concentrations of two constituents and one property that exceeded agricultural-use standards: sulfate (95 percent), chloride (76 percent), and TDS (76 percent). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (24 percent), sulfate (14 percent), chloride (10 percent), and pH (5 percent above upper limit).

7.2.7.4 Madison–Bighorn aquifer

The physical and chemical characteristics of the Madison–Bighorn aquifer in the BHB are described in this section of the report.

Physical Characteristics

The Madison–Bighorn aquifer is a major aquifer in the BHB, and includes the Madison, Darby, and Bighorn aquifers. The Madison–Bighorn aquifer is used as a source of water for domestic, stock, irrigation, and public supply purposes along the eastern margin of the BHB, where lithostratigraphic units composing the aquifer are exposed at land surface or at shallow depth (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). Flowing wells located along the mountain-basin margin may yield large and dependable supplies of potable water, especially those located near anticlines. Water in the aquifer may be under high artesian pressure, with wellhead pressures ranging from 150 to 250 psi in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported the same wellhead pressures as Cooley (1986a) did in outcrop areas, and 600 to 4,900 psi in the basin interior. The aquifer is an important source of public water supply for numerous communities in the BHB. Large volumes of water also are withdrawn from the numerous oilfields developed, mostly in anticlines, throughout the basin (Doremus, 1986).

The Madison–Bighorn aquifer includes the Mississippian-age Madison Limestone (containing the Madison aquifer), the Upper Devonian-age Darby, Three Forks, and Jefferson Formations (containing the Darby aquifer), and the Ordovician-age Bighorn Dolomite (containing the Bighorn aquifer) **(Plate III)**. These formations are hydraulically connected by solution-enlarged joints and fractures (Cooley, 1986a; Doremus, 1986). The Madison–Bighorn aquifer is confined above by low-permeability shales and carbonates of the Amsden Formation (namely the Horsehoe Shale Member) and below by the Gallatin–Gros Ventre confining unit (Stone, 1967; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Several investigators (Libra et al., 1981; Western Water Consultants, Inc., 1982a) consider the Three Forks and Jefferson Formations (considered eastern BHB equivalents of the Darby Formation) to be local confining or leaky confining units between the Bighorn Dolomite and Madison Limestone in parts of the BHB **(Plate III)**. The Madison–Bighorn aquifer is composed of predominantly thick-bedded limestone and dolomite with minor interbedded siltstone and some chert (Cooley, 1986a). The aquifer thickness is highly variable, and depends on the thickness and degree of hydraulic connection between the various lithostratigraphic units composing the aquifer. The Madison Limestone may be cavernous in outcrop. Carbonate beds within the Jefferson Formation are potentially productive in areas with fracturing (Western Water Consultants, Inc., 1983b).

Although hydraulic head may be hundreds of feet greater than that in overlying hydrogeologic units such as the Tensleep aquifer, and although the aquifer generally is confined above by the overlying Amsden Formation and below by the underlying

Gallatin–Gros Ventre confining unit, the Madison–Bighorn aquifer may be in local hydraulic connection with overlying and underlying aquifers at some locations in the BHB. On the basis of the similarity of reservoir fluids in many BHB oilfields, Lawson and Smith (1966) suggested hydraulic connection between geologic units composing the aquifer with overlying geologic units as a result of extensive vertical fracturing in Paleozoic rocks. Stone (1967) also noted the similarity of reservoir fluid chemistry and hydraulic heads in many eastern BHB oilfields, and suggested that faulting and fracturing of Paleozoic rocks in parts of the BHB could provide hydraulic connection with overlying geologic units (for example, Tensleep Sandstone) at some locations. Cooley (1986a, p. 5) noted that these types of vertical fractures appear to allow for "vertical water movement through the upper part of the Amsden Formation from the Madison–Bighorn aquifer to the Tensleep Sandstone near Ten Sleep and Big Trails, where there are anomalous small differences between their potentiometric surfaces." He also noted possible vertical movement of water from underlying aquifers: "The potentiometric contours of the Madison–Bighorn aquifer indicate a slight hydraulic mound near Zeisman dome, and this indicates that there may be some upward movement of water through the Gallatin Limestone and Gros Ventre Formations from the Flathead Sandstone along fractures associated with the doming" (Cooley, 1986a, p. 5). Furthermore, hydraulic continuity of the Madison–Bighorn aquifer can be interrupted in the interior basin by fault-cored anticlines overlying deep basin thrust faults (Huntoon, 1985a; Doremus, 1986). Extensional fractures on fold crests also may increase permeability and vertical hydraulic connection between overlying and underlying aquifers (Doremus, 1986). All these investigators essentially concluded that vertical fracturing associated with anticlines may propagate upward through overlying Paleozoic rocks and damage the hydraulic integrity of aquifers and confining units, allowing for movement of fluids between some Paleozoic formations (implying aquifers) in parts of the BHB.

Permeability in the limestones and dolomites composing the Madison–Bighorn aquifer is both primary and secondary, but the presence of water in the aquifer is controlled primarily by secondary permeability. Primary permeability is minor and attributable to interclast and intercrystalline porosity, whereas secondary permeability predominates due to fractures associated with folds and faults, joints, solution features/cavities, caves, paleokarst, and bedding-plane partings (Libra et al., 1981; Western Water Consultants, Inc., 1982a,b, 1983b; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986, and references therein; Spencer, 1986a). Much of this secondary permeability development is attributable to fractures and associated solution enhancement structurally induced by the folding and faulting of brittle carbonates (Huntoon, 1976; Vietti, 1977; Doremus, 1986).

Permeability characteristics of the Madison–Bighorn aquifer differ between mountain-basin margins and basin interior. Fracture permeability in outcrops along the edges of the eastern basin margin is enhanced by the dissolution of carbonates through infiltration of precipitation (recharge) (Doremus, 1986; Huntoon, 1985a,b, 1993). Permeability decreases basinward as distance from the tectonically fractured Bighorn Mountains and basin margin increases (Bredehoeft, 1964; Huntoon, 1985b, 1993; Doremus, 1986). These investigators note that permeability decreases basinward due to "less fracture permeability in undeformed parts of the basin interior, decreasing solution enhancement of fractures basinward, and re-precipitation of cements in deeper parts of the basin" (Doremus, 1986, p. IV-15). Doremus also noted that solution enhancement of fractures decreases basinward because hydraulic gradients decrease as distance away from recharge areas increases, and carbonate solubility decreases as temperatures increase within the basin interior.

Potentiometric-surface maps of the Madison–Bighorn aquifer in the northeastern BHB were constructed for the same geographic area by Western Water Consultants, Inc. (1982a, Figure 7) and Doremus (1986, Figure 13). The map constructed by Doremus is reproduced herein as **Plate XIV**. Both Western Water Consultants, Inc. and Doremus identified three primary components of regional groundwater flow in the northeastern BHB. The investigators stated that groundwater within the Madison-Bighorn aquifer moves (1) north and northeast into the mapped study area from the southern and western parts of the basin, (2) south from recharge areas in the southern Pryor Mountains, and (3) west and northwest from recharge areas for the Madison aquifer along the western flank of the Bighorn Mountains **(Plate XIV)**. Regional groundwater flow converges on potentiometric-surface depressions associated with large withdrawals and resulting hydraulic head declines in producing oilfields (for example, Byron and Garland oilfields, **Plate XIV**) and springs located in the basin interior (Western Water Consultants, Inc., 1982a; Doremus, 1986). The low hydraulic heads associated with the Byron and Garland anticlines and corresponding oilfields are due to not only fluid withdrawals from the petroleum reservoirs, but also to interformational leakage in fracture and fault zones in the crests of the anticlines (Doremus, 1986). Hydraulic gradients decrease from 300 feet per mile near recharge areas to 30 feet per mile within the basin interior (Doremus, 1986).

The potentiometric surface constructed by Doremus (1986) shows that faults and folds (anticlines) substantially affect groundwater flow in the Madison–Bighorn aquifer and alter the configuration of the potentiometric surface in the northeastern BHB **(Plate XIV)**. Faults may act as barriers to groundwater flow in areas where structural offset is large enough to juxtapose an aquifer against confining units, effectively severing aquifer hydraulic continuity (Western Water Consultants, Inc., 1982a; Huntoon, 1985a; Doremus, 1986). Groundwater also flows along the structural strikes of various anticlines in the northeastern BHB due to "extensional fractures developed in the crests of these anticlines" that "provide zones of secondary enhanced fracture permeabilities which serve as favored hydraulic conduits between recharge areas and the interior of the basin" (Doremus, 1986, p. 36). Doremus also noted that movement between recharge areas and these anticlines was evidenced by the similar water chemistry in anticlines and springs in the recharge areas. In contrast, groundwater flow in other parts of the northeastern BHB may not be continuous from "unsevered recharge areas to the basin interior because faults coring basin anticlines are often barriers to groundwater flow" (Doremus, 1986, p. 37).

Cooley (1986a, Plate 4) constructed a potentiometric-surface map of the Madison–Bighorn aquifer in the Ten Sleep area of the southeastern BHB (reproduced herein as **Plate XV**). Groundwater flow is generally westward in the mapped area, with the steepest gradient adjacent to the Bighorn Mountains. Cooley (1986a) reported that, similarly to the northeastern BHB, the potentiometric surface of the Madison–Bighorn aquifer in the Ten Sleep area also is affected substantially by folds and faults, as well as by withdrawals associated with oilfields. Low hydraulic heads were identified near Big Trails, Ten Sleep, and Hyattville as a result of groundwater discharge from Paleozoic aquifers to shallower aquifers or to the surface.

Well-yield and spring-discharge measurements and other hydraulic properties for the Madison, Darby, and Bighorn aquifers composing the Madison–Bighorn aquifer are summarized in **Plate IX**. Much of the hydraulic data is from petroleum drill-stem tests. These tests typically are conducted in petroleum fields located along the crest of anticlines where fracture zones occur; consequently, values of hydraulic properties in these areas may be higher than those in undeformed parts of the aquifer.

Chemical characteristics

Doremus (1986) evaluated the regional groundwater-quality of the Madison–Bighorn aquifer in the northeastern BHB by examining the factors that affect the quality of groundwater in the aquifer as it moves from recharge areas into the basin interior. TDS concentrations are generally lowest near outcrop areas (assumed recharge areas) and become higher in the basin interior. Doremus concluded that four factors were responsible for changes in groundwater chemistry as water moves from recharge areas along the basin margin into the basin interior: (1) aquifer severing by large basin faults that disrupt the hydraulic continuity of the aquifer and are barriers to groundwater flow from nearby recharge areas; (2) interformational mixing of waters in fracture zones developed in the crests of anticlines; (3) mixing with mineralized waters (large TDS concentrations) from the southern BHB; and (4) movement of groundwater beneath petroleum traps along basin anticlines.

Groundwater-quality data are presented and described for the three aquifers (Madison, Darby, and Bighorn aquifers) composing the Madison–Bighorn aquifer. No data were available to evaluate the groundwater-quality characteristics of the Three Forks and Jefferson Formations, so data for the Darby aquifer is from the Darby Formation. The Darwin Sandstone is included in the Amsden Formation chemical characteristics discussion, above.

7.2.7.4.1 Madison aquifer

The chemical composition of groundwater in the Madison aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from 37 wells and 11 springs. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram L). Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (90 percent of samples) and the remaining waters were slightly to moderately saline (**Appendix E2; Appendix G2**, diagram L; supplementary data tables). TDS concentrations ranged from 173 to 9,980 mg/L, with a median of 232 mg/L.

Concentrations of some properties and constituents in water from the Madison aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of several properties and constituents exceeded health-based standards (USEPA MCLs and HALs): gross alpha radioactivity (17 percent of samples analyzed for the constituent), radium-226 plus radium-228 (17 percent), lead (12 percent of samples), boron (8 percent), and fluoride (5 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (25 percent), TDS (12 percent), sulfate (10 percent), fluoride (8 percent), pH (3 percent below lower limit), and chloride (2 percent).

The chemical composition of groundwater in the Madison aquifer also was characterized and the quality evaluated on the basis of 201 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram I). TDS concentrations from produced-water samples were highly variable and ranged from fresh to briny, and the concentrations indicated that most of the water was moderately saline (55 percent) (**Appendix F2; Appendix H2**, diagram I; supplementary data tables). TDS concentrations ranged from 319 to 142,000 mg/L, with a median of 3,370 mg/L.

Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of two constituents that always exceeded health-based standards (USEPA MCLs and HALs): fluoride (100 percent) and strontium (100 percent). The produced-water samples had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: fluoride (100 percent), filtered iron (100 percent), TDS (99 percent), sulfate (95 percent), chloride (47 percent), and pH (6 percent below lower limit and 3 percent above upper limit). TDS concentrations in produced-water samples from the Madison aquifer rarely exceeded the State of Wyoming Class IV standard (2 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were gross alpha radioactivity (17 percent), radium-226 plus radium-228 (17 percent), sulfate (10 percent), boron (8 percent), TDS (7 percent), SAR (4 percent), and chloride (2 percent). The properties and constituents that had concentrations greater than livestock-use standards were gross alpha radioactivity (17 percent), radium-226 plus radium-228 (17 percent), pH (3 percent below lower limit), TDS (2 percent), and sulfate (2 percent).

The produced-water samples from the Madison aquifer generally had concentrations of several properties and constituents that exceeded agricultural-use standards: sulfate (96 percent), chloride (84 percent), TDS (83 percent), filtered iron (50 percent), and pH (1 percent above upper limit). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (8 percent), chloride (5 percent), pH (6 percent below lower limit and 3 percent above upper limit), and sulfate (3 percent).

7.2.7.4.2 Darby aquifer

The chemical composition of groundwater in the Darby aquifer in the BHB was characterized and the quality evaluated on the basis of two produced-water samples from wells. Individual constituent concentrations are listed in **Appendix F2**. TDS concentrations from both produced-water samples (3,280 and 6,760 mg/L) indicated that the waters were moderately saline (**Appendix F2**).

Concentrations of some properties and constituents in water from the Darby aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had concentrations of one property and two constituents that exceeded aesthetic standards (USEPA MCLs and HALs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), and chloride (50 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Both produced-water samples had concentrations of one property (TDS) and two constituents (chloride and sulfate) that exceeded agricultural-use standards. Concentrations of TDS and sulfate exceeded livestock use standards in one of the two produced-water samples.

7.2.7.4.3 Bighorn aquifer

The chemical composition of groundwater in the Bighorn aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from two wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. TDS concentrations were variable and indicated that most waters were fresh (83 percent of samples) and the remaining waters were moderately saline (**Appendix E2**; supplementary data tables). TDS concentrations ranged from 136 to 3,410 mg/L, with a median of 230 mg/L.

Concentrations of some properties and constituents in water from the Bighorn aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): boron (17 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (20 percent below lower limit and 20 percent above upper limit), TDS (17 percent), chloride (17 percent), fluoride (17 percent), and sulfate (17 percent).

The chemical composition of groundwater in the Bighorn aquifer also was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2**. TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, and the concentrations indicated that most waters were moderately saline (55 percent) (**Appendix F2; Appendix H2**, Figure J; supplementary data tables). TDS concentrations ranged from 1,180 to 14,300 mg/L, with a median of 3,460 mg/L.

Most water-quality analyses available for the Bighorn aquifer were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had available USEPA MCLs or HALs, so comparisons could not be made to health-based standards. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: sulfate (100 percent), TDS (100 percent), chloride (73 percent), and pH (11 percent below lower limit). TDS concentrations in produced-water samples from the Bighorn aquifer infrequently exceeded State of Wyoming Class IV standards (9 percent).

Concentrations of some properties and constituents in environmental water samples exceeded State of Wyoming standards for agricultural and livestock use in the BHB. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were chloride (17 percent), sulfate (17 percent), TDS (17 percent), and boron (17 percent). Values of one characteristic were greater than the livestock-use standard: pH (20 percent below lower limit and 20 percent above upper limit).

The produced-water samples generally had concentrations of one property and two constituents that always or frequently exceeded agricultural-use standards: sulfate (100 percent), TDS (91 percent), and chloride (82 percent). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (18 percent), pH (11 percent below lower limit), chloride (9 percent), and sulfate (9 percent).

7.2.7.5 Recharge, discharge, and groundwater movement

Aquifers in the Paleozoic aquifer system in the BHB are recharged primarily from precipitation (rain and snow melt) and streamflow infiltrating exposed outcrops along the BHB mountain-basin margin (Lowry et al., 1976; Libra et al., 1981; Cooley, 1984, 1986a; Huntoon, 1985a,b; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). Upturned beds of Paleozoic rocks are common, and substantial differences in streamflow losses or gains have been observed between karst and non-karst areas (Huntoon, 1985a,b; Plafcan et al., 1993). In the Trapper-Medicine Lodge area between Shell and Hyattville, some streams reportedly lose all flow to underlying karst developed in the Madison-Bighorn aquifer (Huntoon, 1985a,b). Streamflow data from Druse et al. (1989) led Plafcan et al. (1993) to conclude that recharge to Paleozoic aquifers from streams was variable along the western flank of the Bighorn Mountains. Plafcan et al. (1993, p. 49) also speculated that "in non-karst areas, direct infiltration of precipitation into outcrops is probably a more substantial recharge component than that contributed by losing streams."

Potentiometric-surface maps presented previously herein indicate that groundwater in the Paleozoic aquifers generally flows away from the outcrop areas (source of recharge) on the basin margins and toward the center of the BHB (Bighorn Basin). Groundwater near the Bighorn River flows northward toward Montana on some maps. Many investigators speculate that groundwater flow in other aquifers in the BHB is similar to flow in the Tensleep aquifer (for example, Lowry et al., 1976; Libra et al., 1981; Cooley, 1984, 1986a; Huntoon, 1985a). However, much of the water that enters the aquifers as recharge does not move into the basin: the homocline from the Bighorn Mountains to the BHB is discontinuous due to numerous thrust and high-angle coring reverse faults (Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a; Huntoon (1985a,b,c, 1993; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). These coring faults, commonly associated with anticlines, can disrupt hydraulic continuity of the aquifers along the basin-mountain margin. This faulting may create hydraulically unconnected groundwater systems in the foot and hanging walls where permeable rocks are faulted against impermeable rocks, and thus prevent movement of water into the basin interior.

The work of Huntoon (1985a), as well as the published work of his graduate students (Doremus, 1986; Jarvis, 1986; Spencer, 1986a) and contemporary investigators (Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a), represents greatly improved understanding of the effects of folding and faulting on groundwater flow in Paleozoic aquifers (Tensleep and Madison–Bighorn aquifers) of the BHB – improved understanding that is applicable to aquifers in other Wyoming structural basins (see Huntoon, 1993). Collectively, these investigators noted that the numerous folds and faults located along the eastern homoclinal BHB margin, depending upon their spatial orientation, may act as (1) hydraulic conduits that connect recharge areas along the basin margin to the basin interior if oriented oblique to basin margins, or (2) act as hydraulic barriers that sever the hydraulic continuity between recharge areas along the basin margin and basin interior if oriented parallel to basin margins (depending on the amount of fault displacement). These investigators also noted that areas with tight folding and extensive faulting commonly have enhanced secondary permeability from fractures and may yield greater volumes of water than undeformed areas, an advancement subsequently exploited by those attempting to locate high-yielding public-supply wells in the Paleozoic aquifer system in the BHB. In addition, these investigators noted that groundwater quality in the Paleozoic aquifer system varies relative to location along folds and faults, as well as to proximity to the basin margin. Groundwater within the

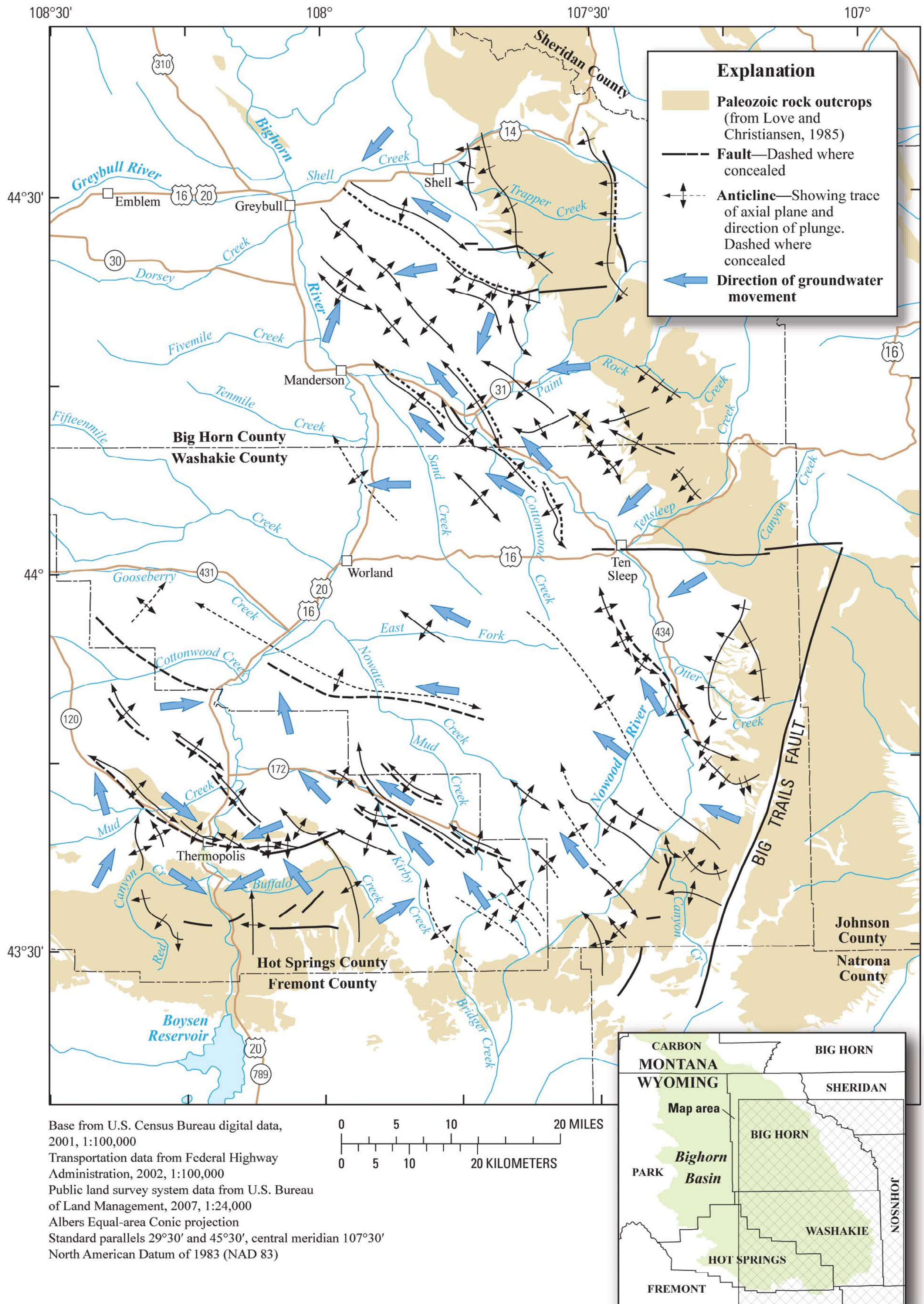


Figure 7-11. Generalized groundwater movement for the Paleozoic aquifer system in the Bighorn Basin, Wyoming (modified from Jarvis, 1986a, Figure 18).

footwalls of fault-severed anticlines is generally of poor quality, whereas groundwater in the hanging wall is generally of good quality (or at least better than in the footwall). Groundwater quality near outcrops along basin margins (assumed to represent recharge areas) is generally good and generally becomes poor (more mineralized) as the water moves into the basin interior.

Jarvis (1986, Figure 18) used this improved understanding to graphically show how generalized groundwater flow in Paleozoic aquifers in the BHB is structurally controlled by folding and faulting (modified herein as **Figure 7-11**). Groundwater flows around lateral terminations of faults oriented parallel to the basin margin, whereas groundwater flows along and parallel to structural trends oriented oblique to the basin margin **(Figure 7-11)**. In addition, major coring reverse faults sever hydraulic conductivity between recharge areas (represented by outcrop areas) and the basin interior.

Discharge from aquifers in the Paleozoic aquifer system is both natural and anthropogenic. The Tensleep aquifer predevelopment (prior to oilfield development) potentiometric-surface map of Bredehoeft and Bennett (1972) indicates discharge at outcrops along the Bighorn River (Lowry et al., 1976; Plafcan et al., 1993). The Bighorn River has cut through numerous anticlines in the basin interior, resulting in natural discharge from now-exposed Paleozoic rocks (Libra et al., 1981; Egemeier, 1973; Lowry et al., 1976; Plafcan et al., 1993). For example, Lowry et al. (1976, Sheet 1) noted that the Bighorn River has "eroded completely through the Tensleep Sandstone at the Wyoming-Montana border," and "therefore, water does not move northward out of Wyoming in the Tensleep Sandstone." Thermal springs from the Madison-Bighorn and (or) Tensleep aquifers reportedly discharge from the Sheep Mountain, Little Sheep Mountain, and Thermopolis/Warm Springs anticlines (Libra et al., 1981; Egemeier, 1973; Plafcan et al., 1993). Libra et al. (1981) reported spring flows from Paleozoic rocks along the Rattlesnake Mountain anticline west of Cody. Discharge from the Paleozoic aquifers in the Nowood River area was reported by Cooley and Head (1979b); they reported that water from the Tensleep aquifer moves upward along solution-collapse features in Phosphoria Formation evaporites and discharges as seeps and springs or as recharge to Quaternary unconsolidated alluvial deposits overlying the Phosphoria Formation. Other points of natural discharge from aquifers in the Paleozoic aquifer system include numerous springs and gaining streams. The primary anthropogenic sources of discharge from aquifers in the Paleozoic aquifer system are large-capacity public-supply, irrigation, and oilfield wells (Lowry et al., 1976; Libra et al., 1981; Western Water Consultants, Inc., 1982a,b; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a; Plafcan et al., 1993).

7.2.8 Gallatin–Gros Ventre confining unit

The physical and chemical characteristics of the Gallatin–Gros Ventre confining unit in the BHB are described in this section of the report.

Physical characteristics

The Gallatin–Gros Ventre confining unit is composed of the Cambrian-age Gallatin Limestone and Gros Ventre Formation. The thick unit confines and separates the underlying Flathead aquifer from the overlying Madison-Bighorn aquifer **(Plate III)**. The reported thickness of the confining unit ranges from about 800 to 1,200 ft (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Gallatin Limestone is composed of glauconitic gray-green shale and pebbly limestone with minor interbedded sandstone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). The Gros Ventre Formation is composed of glauconitic and sandy limestone with interbedded gray-green shale, sandy limestone, and uncommon interbedded limy sandstone (Lowry et al., 1976; Libra et al., 1981; Plafcan et al., 1993). Although both formations are confining units for aquifers in the Paleozoic aquifer system, both may yield small quantities of water to wells and springs at some locations in the BHB, especially from interbedded limestones and sandstones (Libra et al., 1981; Jarvis, 1986). Little hydrogeologic information is available describing the Gallatin–Gros Ventre confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for the Gallatin and Gros Vertre confining units are summarized on **Plate IX**.

Chemical characteristics

No groundwater samples were available to evaluate the groundwater-quality characteristics of the Gallatin confining unit. The chemical composition of groundwater in the Gros Ventre confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations for those samples are listed in Appendix E2. TDS concentrations indicated that water from the spring (210 mg/L) was fresh, whereas water from the well (3,010 mg/L) was moderately saline.

Concentrations of some properties and constituents in the Gros Ventre Formation in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use with the exception of the boron concentration in the well sample. Concentrations of one property (TDS) and four constituents (chloride, fluoride, filtered iron, and sulfate) exceeded aesthetic standards (USEPA SMCLs) for domestic use in the water sample from the well.

Concentrations of a few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. One property (TDS) and two constituents (chloride and sulfate) in the environmental water sample from the well had concentrations greater than agricultural-use standards. No property or constituent had concentrations that exceeded State of Wyoming livestock standards.

7.2.9 Flathead aquifer

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

Physical characteristics

The Flathead aquifer is composed of the Cambrian-age Flathead Sandstone **(Plate III)**. The Flathead aquifer is a major aquifer in the BHB. The Flathead Sandstone consists of fine- to medium-grained arkosic and quartzitic sandstone with some interbedded shale in the upper part (Libra et al., 1981; Cooley, 1986a). The Flathead aquifer is confined above by thick low-permeability shales of the overlying Gallatin–Gros Ventre confining unit and below by nonporous igneous and metasedimentary rocks of the Precambrian basement that act as a basal confining unit to all aquifers and aquifer systems in the BHB (Stone, 1967; Vietti, 1977; Libra et al., 1981; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. The aquifer is a source of water for stock and irrigation purposes along the eastern margin of the BHB, where the Flathead Sandstone is exposed at land surface or at shallow depth (Libra et al., 1981; Cooley, 1986a; Doremus, 1986; Plafcan et al., 1993). The Flathead Sandstone ranges from 100 to 200 ft in thickness, but is absent in the northeastern BHB (Lowry et al., 1976; Cooley, 1986a).

Water in the Flathead aquifer may be under very high artesian pressure, with wellhead pressures reportedly as high as 472 psi in the Ten Sleep area (Cooley, 1986a). Jarvis (1986, Figure 9, and references therein) reported wellhead pressures of greater than 400 psi in outcrop areas, and wellhead pressures ranging from 2,600 to 3,200 psi in the basin interior. Flowing wells located along the mountain-basin margin may yield large and dependable supplies of potable water. Cooley (1986a) noted decreased shut-in pressure for wells completed in the aquifer near Ten Sleep, and he attributed the decreases to continuous discharge of water from wells completed in the aquifer. Although considered a potentially very good source of groundwater for development by most investigators, the aquifer is rarely developed as a source of water because of deep burial throughout most of the BHB.

Porosity is intergranular, but secondary permeability is present as a result of fracturing near folds and faults (Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a). In fact, Cooley (1986a, p. 4) stated that "water movement in the sandstone seems to be controlled principally by fracturing, judging from the general tightness of the unfractured part of the sandstone where exposed." Recharge to the Flathead aquifer is likely from infiltration of precipitation and streamflow in outcrop areas. Well-yield and spring-discharge measurements and other hydraulic properties for the Flathead aquifer are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Flathead aquifer in the BHB was characterized and the quality evaluated on the basis of environmental water samples from eight wells and four springs. Summary statistics calculated for available constituents are listed in **Appendix E2**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G2**, diagram M). TDS concentrations were variable and indicated that waters were fresh (**Appendix E2; Appendix G2,** diagram M; supplementary data tables). TDS concentrations ranged from 58 to 443 mg/L, with a median of 163 mg/L.

The chemical composition of groundwater in the Flathead aquifer also was characterized and the quality evaluated on the basis of 13 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F2.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H2**, diagram K). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline; however, concentrations indicated that most waters were moderately saline (69 percent) (**Appendix F2; Appendix H2,** diagram K; supplementary data tables). TDS concentrations ranged from 2,730 to 13,300 mg/L, with a median of 3,950 mg/L.

Concentrations of some properties and constituents in the Flathead aquifer in the BHB approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (USEPA MCLs and HALs): barium (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: filtered iron (20 percent), manganese (20 percent), pH (8 percent above upper limit), and aluminum (6 percent exceeded lower and upper limits).

Most water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples had a concentration of two constituents in one sample that exceeded health-based standards (USEPA MCLs and HALs):

radium-226 plus radium-228 and strontium. The produced-water samples had concentrations of several properties and constituents that always exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent), chloride (100 percent), and sulfate (100 percent). TDS concentrations in 15 percent of produced-water samples from the Flathead aquifer exceeded State of Wyoming Class IV standards.

Concentrations of a few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the BHB. The constituent and property in environmental water samples that had concentrations greater than agricultural-use standards were chromium (100 percent) and SAR (9 percent). Values of one property were greater than livestock-use standards: pH (8 percent above upper limit).

The produced-water samples had concentrations of two constituents and one property that always exceeded agricultural-use standards: chloride (100 percent), sulfate (100 percent), and TDS (100 percent). The produced-water samples had concentrations of one characteristic and one constituent that infrequently exceeded livestock-use standards: TDS (15 percent) and chloride (15 percent).

7.2.10 Precambrian basal confining unit

The physical and chemical characteristics of the Precambrian basal confining unit in the BHB are described in this section of the report.

Physical characteristics

Undifferentiated nonporous igneous and metasedimentary rocks of the Precambrian basement act as a basal confining unit to the Flathead aquifer, as well as to all aquifers and aquifer systems in the BHB (Stone, 1967; Vietti, 1977; Libra et al., 1981; Cooley, 1984, 1986a; Doremus, 1986; Jarvis, 1986; Spencer, 1986a) **(Plate III)**. Little is known about Precambrian rocks at depth in the BHB; however, wells are completed locally for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out – permeability is attributable to weathered, fractured, or faulted rocks (Lowry et al., 1976; Libra et al., 1981). Lowry et al. (1976) noted that the shallow permeable zone typically is less than 100 ft deep. The investigators also noted that fractures decrease in both size and number with depth. Well-yield and spring-discharge measurements and other hydraulic properties for the Precambrian basal confining unit are summarized on **Plate IX**.

Chemical characteristics

The chemical composition of groundwater in the Precambrian basal confining unit in the BHB was characterized and the quality evaluated on the basis of environmental water samples from three springs. Individual constituent concentrations are listed in **Appendix E2**. TDS concentrations indicated that the waters were fresh (**Appendix E2**; supplementary data tables). On the basis of the few properties and constituents analyzed for, water from Precambrian rocks in the BHB was suitable for most uses. Concentrations of one constituent and one property exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (50 percent of samples analyzed for the constituent) and pH (33 percent above upper limit). Concentrations of one property exceeded State of Wyoming standards for agricultural use: pH (33 percent above upper limit). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

7.3 Absaroka Range and Yellowstone Volcanic Area

The physical and chemical characteristics of aquifers in the Absaroka Range and Yellowstone volcanic area (AYV) are described in this section of the report.

Physical characteristics

The AYV (generally the “Absaroka–Yellowstone volcanics” of **Figure 7-1**, Quaternary aquifers within them, and the Tertiary, Mesozoic, and Paleozoic aquifers just east of them) is sparsely populated and has no major population centers. Much of the area is within the boundary of Yellowstone National Park. Consequently, the demand for water supply generally is small, and is limited to visiting tourists, park employees, and residents of areas surrounding the park. Because the population is dispersed, much of this demand is met with groundwater. However, aquifers that can provide a water supply sufficient in quantity and quality may not be present at many locations.

Three types of aquifers are present in the AYV – Quaternary unconsolidated-deposit aquifers, Quaternary and Tertiary volcanic-rock aquifers, and Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers (Lowry and Gordon, 1964; Cox, 1973b, 1976). The areal extents of lithostratigraphic units composing these hydrogeologic units are shown on **Plate I**. These aquifers are utilized primarily for domestic or public supply use. Many of the Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers are buried beneath Quaternary-age unconsolidated deposits and Quaternary and Tertiary-age volcanic rocks. Most wells are completed in Quaternary unconsolidated-deposit aquifers in the AYV, and few, if any, wells are completed in the Quaternary and Tertiary volcanic-rock aquifers even though they crop out throughout most of the area (Cox, 1976). Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers are rarely utilized for water supply, and little or no information is available describing their hydrogeologic characteristics within the AYV.

Quaternary unconsolidated-deposit aquifers in the AYV are composed typically of alluvium (and colluvium), lacustrine deposits, or glacial deposits (Cox, 1976). Landslide deposits are saturated in some locations and yield water to numerous springs (Cox, 1976). Locally, Quaternary unconsolidated-deposit aquifers commonly overlie Quaternary and Tertiary volcanic-rock aquifers and likely are in direct hydraulic connection with them (Whitehead, 1996). Groundwater in Quaternary unconsolidated-deposit aquifers typically is unconfined. Many wells completed in Quaternary unconsolidated-deposit aquifers in the Yellowstone National Park area are located close to and along streams or lakes (Cox, 1973b, 1976). Such aquifers commonly are in hydraulic connection with and receive recharge from the adjacent stream or lake (Cox, 1973b, 1976). Well-yield and spring-discharge measurements for unconsolidated deposits in the AYV (alluvial aquifers, aquifers in landslide deposits, aquifers in lacustrine deposits, glacial-deposit aquifers) are summarized on **Plate IX**.

Quaternary and Tertiary volcanic-rock aquifers are composed of extrusive igneous rocks (primarily basalt and rhyolite) and beds of tuff and volcanic ash. These aquifers are essentially undeveloped; with the exception of spring discharges, little or no quantitative hydrogeologic information is available to characterize and evaluate the development potential of these aquifers **(Plate IX)**. Investigations related to these aquifers have been mainly of thermal waters and related features in Yellowstone National Park (Ball, McCleskey, et al., 2002; Ball, Nordstrom, Cunningham, et al., 1998; Ball, Nordstrom, Jenne, and Vivit, 1998; Ball, Nordstrom, McCleskey, et al., 2001; Bargar, 1978; Fix, 1949; Fournier, Christianson, et al., 1994, Fournier and Morgenstern, 1971; Fournier and Rowe, 1966; Fournier and Truesdell, 1970; Friedman and Norton, 1982, 1990; Gooch and Whitfield, 1888; Merler, 1964; Marler and White, 1975; Morey et al., 1961; Pearson and Truesdell, 1978; Rowe, Fournier, and Morey, 1965, 1973; Rye and Truesdell, 1993; Schlundt and Moore, 1909; Stauffer, Jenne, and Ball, 1980; Stauffer and Thompson, 1978, 1984; Stearns, Stearns, and Waring, 1937; Thompson and Hutchinson, 1981; Thompson, Presser, et al., 1975; Thompson and Sandhya, 1979; Truesdell and Fournier, 1976a,b; Truesdell, Nathenson, and Rye, 1977; Truesdell, Rye, et al., 1978; Truesdell and Thompson, 1982; Weed, 1889; White, 1991; White, Hutchinson, and Keith, 1988). Cox (1976, Sheet 1) speculated on the potential well yield of the various Quaternary and Tertiary volcanic-rock aquifers and noted that the Yellowstone Group "may yield a few tens of gallons per minute per well from porous and fracture zones" (rhyolitic ash, welded tuff, lava flows, breccia, and volcanic glass) or "may yield a few tens of gallons per minute per well from brecciated zones and fractures" (basalt lava flows). Cox (1976, Sheet 1) also speculated that the Absaroka Volcanic Supergroup, composed of andesitic, basaltic, and dacitic volcaniclastic rocks, "probably would not yield more than a few gallons per minute per well." Well-yield and spring-discharge measurements for Quaternary and Tertiary volcanic-rock aquifers in the AYV are summarized on **Plate IX**.

Chemical characteristics

The chemical characteristics of Quaternary unconsolidated-deposit aquifers, Quaternary and Tertiary volcanic-rock aquifers, and Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers in the AYV are described in the following sections.

7.3.1 Quaternary unconsolidated-deposit aquifers

The chemical characteristics of Quaternary unconsolidated-deposit aquifers (alluvial aquifers, aquifers in lacustrine deposits, and glacial-deposit aquifers) in the AYV are described in this section of the report. Groundwater-quality samples from springs discharging from aquifers in landslide deposits and hydrothermal deposits also are described.

Alluvial aquifers

The chemical composition of groundwater in alluvial aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 33 wells and 5 springs. Summary statistics calculated for available constituents are listed in **Appendix E3.** Major-ion composition in relation to TDS is shown on a trilinear diagram **(Appendix G3**, diagram A). TDS concentrations were variable and indicated that most waters were fresh (89 percent of samples) and the remaining waters were slightly saline (Appendix E3; Appendix G3, diagram A; supplementary data tables). TDS concentrations ranged from 57 to 1,550 mg/L, with a median of 182 mg/L.

Concentrations of some properties and constituents in water from alluvial aquifers in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards (USEPA MCLs and HALs): arsenic (60 percent of samples analyzed for the constituent), fluoride (42 percent), antimony (40 percent), boron (14 percent), molybdenum (11 percent), lead (10 percent), and nitrate plus nitrite (9 percent). Concentrations of some properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (58 percent exceeded lower limit), fluoride (54 percent), pH (34 percent below lower limit and 3 percent above upper limit), manganese (25 percent), filtered iron (20 percent), TDS (18 percent), and chloride (11 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were arsenic (30 percent), SAR (21 percent), lithium (18 percent), manganese (15 percent), chloride (13 percent), boron (21 percent), pH (3 percent below lower limit and 3 percent above upper limit), and filtered iron (3 percent). Properties and constituents that had concentrations greater than livestock-use standards were pH (34 percent below lower limit and 3 percent above upper limit), arsenic (30 percent), and boron (14 percent).

Aquifers in landslide deposits

The chemical composition of water from aquifers in landslide deposits in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (158 mg/L) indicated that the water was fresh. On the basis of the properties and constituents analyzed, the quality of water from landslide deposits in the AYV was suitable for most uses. No properties or constituents had concentrations that approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

Aquifers in lacustrine deposits

The chemical composition of water from aquifers in lacustrine deposits in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 38 wells. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram B). TDS concentrations were variable and indicated that waters were fresh (**Appendix E3**; **Appendix G3**, diagram B; supplementary data tables). TDS concentrations ranged from 65 to 340 mg/L, with a median of 99.5 mg/L.

Concentrations of some properties and constituents in water from aquifers in lacustrine deposits in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): arsenic (100 percent of samples analyzed for the constituent), nitrate plus nitrite (7 percent), and fluoride (5 percent). Concentrations of one property and several constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (16 percent below lower limit), manganese (16 percent), filtered iron (11 percent), and fluoride (8 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Concentrations of one constituent in environmental water samples were greater than an agricultural-use standard: manganese (5 percent). Values for one property were less than a livestock-use standard: pH (16 percent below lower limit).

Aquifers in hydrothermal deposits

The chemical composition of water from aquifers in hydrothermal deposits in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E3**. The TDS concentration (568 mg/L) indicated that the water was fresh.

Concentrations of some properties and constituents in hydrothermal deposits in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The environmental water generally was suitable for domestic use. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (below lower limit), TDS, aluminum (exceeded lower and upper limits), manganese, and sulfate.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the AYV. Properties and constituents in the environmental water sample that had concentrations greater than agricultural-use standards were pH (below lower limit), SAR, aluminum, boron, and sulfate. One property (pH, below lower limit) and one constituent (aluminum) had concentrations greater than livestock-use standards.

Glacial-deposit aquifers

The chemical composition of groundwater in glacial-deposit aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from 14 wells and three springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram C). TDS concentrations indicated that the waters were fresh (**Appendix E3; Appendix G3**, diagram C; supplementary data tables). TDS concentrations ranged from 112 to 933 mg/L, with a median of 223 mg/L.

Concentrations of some properties and constituents in the glacial-deposit aquifers in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of a few constituents exceeded health-based standards (USEPA MCLs and HALs): ammonia (38 percent of samples analyzed for the constituent), nitrate plus nitrite (30 percent), and fluoride (6 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: manganese (100 percent), pH (53 percent below lower limit), fluoride (35 percent), filtered iron (29 percent), sulfate (6 percent), and TDS (6 percent).

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were manganese (88 percent), boron (14 percent), SAR (10 percent), filtered iron (7 percent), and sulfate (6 percent). Values for one property were less than a livestock-use standard: pH (53 percent below lower limit).

7.3.2 Quaternary and Tertiary volcanic-rock aquifers

The chemical characteristics of Quaternary and Tertiary volcanic-rock aquifers in rhyolite flows, tuff, and intrusive igneous rocks; the Yellowstone Group; and the Absaroka Volcanic Supergroup in the AYV are described in this section of the report.

7.3.2.1 Aquifers in rhyolite flows, tuff, and intrusive igneous rocks

The chemical composition of water from aquifers in rhyolite flows, tuff, and intrusive igneous rocks in the AYV was characterized and the quality evaluated on the basis of environmental water samples from one test hole and nine springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram D). TDS concentrations indicated that waters were fresh (**Appendix E3; Appendix G3**, diagram D; supplementary data tables). TDS concentrations ranged from 40 to 808 mg/L, with a median of 93 mg/L.

Concentrations of some characteristics and constituents in water from aquifers in rhyolite flows, tuff, and intrusive igneous rocks in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of one constituent exceeded health-based standards (MCLs and HALs): fluoride (100 percent of samples analyzed for the constituent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: fluoride (100 percent of samples analyzed for the constituent), pH (60 percent below lower limit), aluminum (17 percent exceeded lower and upper limits), manganese (12 percent), chloride (10 percent), and TDS (10 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were lithium (12 percent), SAR (12 percent), and chloride (10 percent). Values for one property (pH) were less than livestock-use standards (60 percent below lower limit).

7.3.2.2 Yellowstone Group aquifers

The chemical composition of groundwater in the Yellowstone Group aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from two wells, one test hole, and 23 springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram E). TDS concentrations were variable and indicated that most waters were fresh (62 percent of samples) and the remaining waters were slightly saline (**Appendix E3; Appendix G3**, diagram E; supplementary data tables). TDS concentrations ranged from 43 to 2,130 mg/L, with a median of 563 mg/L.

Concentrations of some properties and constituents in water from the Yellowstone Group aquifers in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards (USEPA MCLs and HALs): boron (50 percent of samples analyzed for the constituent), arsenic (47 percent), molybdenum (33 percent), antimony (28 percent), and beryllium (4 percent). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: pH (69 percent below lower limit), aluminum (66 percent above lower limit and 23 percent above upper limit), TDS (50 percent), chloride (38 percent), filtered iron (19 percent), manganese (15 percent), and sulfate (8 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were boron (50 percent), chloride (46 percent), SAR (42 percent), arsenic (32 percent), lithium (27 percent), pH (15 percent below lower limit), TDS (12 percent), manganese (12 percent), sulfate (8 percent), aluminum (5 percent), and filtered iron (4 percent). Properties and constituents that had concentrations greater than livestock-use standards were pH (69 percent below lower limit), arsenic (32 percent), boron (32 percent), and aluminum (5 percent).

7.3.2.3 Absaroka Volcanic Supergroup aquifers

The chemical composition of groundwater in the Absaroka Volcanic Supergroup aquifers in the AYV was characterized and the quality evaluated on the basis of environmental water samples from two wells and eight springs. Summary statistics calculated for available constituents are listed in **Appendix E3**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G3**, diagram F). TDS concentrations indicated that waters were fresh (**Appendix E3**; **Appendix G3**, diagram F; supplementary data tables). TDS concentrations ranged from 101 to 265 mg/L, with a median of 176 mg/L.

Concentrations of some properties and constituents in water from the Absaroka Volcanic Supergroup aquifers in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: aluminum (50 percent of samples analyzed for the constituent exceeded lower and (or) upper limits). No properties or constituents approached or exceeded applicable State of Wyoming agriculture or livestock water-quality standards.

7.3.3 Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers

The chemical characteristics of groundwater in Paleozoic, Mesozoic, and Cenozoic sedimentary-rock aquifers in the AYV are described in this section of the report. Most of the groundwater-quality data from these aquifers were obtained from produced-water samples collected from wells located along the periphery of the AYV outside areas of volcanic rocks (**Figure 7-1**: Tertiary, Mesozoic, and Paleozoic aquifers just east of the Absaroka–Yellowstone volcanics).

7.3.3.1 Willwood aquifer

The chemical composition of groundwater in the Willwood aquifer in the AYV was characterized and the quality evaluated on the basis of environmental water samples from three wells. Summary statistics calculated for available constituents are listed in **Appendix E3**. TDS concentrations indicated that the waters were fresh. TDS concentrations ranged from 220 to 398 mg/L, with a median of 326 mg/L.

Concentrations of some properties and constituents in water from the Willwood aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based (USEPA MCLs and HALs) and agricultural standards, all waters were suitable for domestic and agricultural use. Values of one property exceeded aesthetic standards (USEPA SMCLs) for domestic use and standards for livestock use: (pH) (33 percent of samples analyzed for the property had values above upper limits for domestic and livestock use).

7.3.3.2 Frontier aquifer

The chemical composition of groundwater in the Frontier aquifer in the AYV was characterized and the quality evaluated on the basis of three produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3**. TDS concentrations from produced-water samples indicated that the waters were slightly saline. TDS concentrations ranged from 1,420 to 1,870 mg/L, with a median of 1,800 mg/L.

Concentrations of some properties and constituents in water from the Frontier aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and one constituent that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the characteristic) and chloride (33 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples generally had concentrations of two constituents that exceeded agricultural-use standards: chloride (67 percent) and sulfate (33 percent). No properties or constituents had concentrations that exceeded livestock-use standards.

7.3.3.3 Cloverly aquifer

The chemical composition of groundwater in the Cloverly aquifer in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (1,850 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in water from the Cloverly aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between sample concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of one property (TDS) and one constituent (sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Few concentrations exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had a concentration of one constituent (sulfate) that exceeded the agricultural-use standard. None of the concentrations in the produced water sample exceeded livestock-use standards.

7.3.3.4 Morrison confining unit and aquifer

The chemical composition of groundwater in the Morrison confining unit and aquifer in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F3**. The TDS concentration (1,390 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in water from the Morrison confining unit in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between sample concentrations and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of two properties (pH and TDS) and one constituent (sulfate) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of few properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had concentrations of one constituent (sulfate) that exceeded agricultural-use standards and values of one property (pH) above the livestock-use standard.

7.3.3.5 Chugwater aquifer

The chemical composition of groundwater in the Chugwater aquifer in the AYV was characterized and the quality evaluated on the basis of 11 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, diagram A). TDS concentrations from produced-water samples were variable and ranged from slightly to very saline, and most waters were very saline (73 percent) (**Appendix F3; Appendix H3**, diagram A; supplementary data tables). TDS concentrations ranged from 1,600 to 32,800 mg/L, with a median of 13,100 mg/L.

Concentrations of some properties and constituents in water from the Chugwater aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and two constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (100 percent), and chloride (82 percent). TDS concentration in 73 percent of the produeced-water samples from the Chugwater aquifer exceeded the State of Wyoming Class IV standards.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples generally had concentrations of two constituents and one property that exceeded agricultural-use standards: chloride (100 percent), sulfate (100 percent), and TDS (91 percent). The produced-water samples generally had concentrations of one property and two constituents that exceeded livestock-use standards: TDS (91 percent), sulfate (91 percent), and chloride (18 percent).

7.3.3.6 Phosphoria aquifer and confining unit

The chemical composition of groundwater in the Phosphoria aquifer in the AYV was characterized and the quality evaluated on the basis of 14 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F3.** Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H3**, diagram B). TDS concentrations indicated that most waters were moderately saline (64 percent of samples) and the remaining waters were slightly saline (**Appendix F3; Appendix H3**, diagram B; supplementary data tables). TDS concentrations ranged from 1,050 to 8,850 mg/L, with a median of 3,810 mg/L.

Concentrations of some properties and constituents in water from the Phosphoria aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality samples were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water samples generally had concentrations of one property and two constituents that frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed for the property), sulfate (93 percent), and chloride (57 percent).

Concentrations of some properties and constituents exceeded

State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples had concentrations of two constituents and one property that frequently exceeded agricultural-use standards: chloride (93 percent), sulfate (93 percent), and TDS (79 percent). The produced-water samples had concentrations of one property and one constituent that exceeded livestock-use standards: TDS (14 percent) and sulfate (14 percent).

7.3.3.7 Tensleep aquifer

The chemical composition of groundwater in the Tensleep aquifer in the AYV was characterized and the quality evaluated on the basis of nine produced-water samples from wells. Summary statistics calculated for available constituents are listed in Appendix F3. TDS concentrations indicated that most waters were moderately saline (89 percent of samples) and the remaining waters were slightly saline (**Appendix F3**; supplementary data tables). TDS concentrations ranged from 1,060 to 7,950 mg/L, with a median of 4,570 mg/L.

Concentrations of some properties and constituents in water from the Tensleep aquifer in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. The water-quality samples were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made.

The produced-water samples had concentrations of one property and two constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (100 percent of samples analyzed the property), sulfate (89 percent), and chloride (44 percent).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water samples had concentrations of two constituents and one property that exceeded agricultural-use standards: chloride (89 percent), sulfate (89 percent), and TDS (89 percent). The produced-water samples had concentrations of one characteristic and one constituent that exceeded livestock-use standards: TDS (22 percent) and sulfate (11 percent).

7.3.3.8 Amsden confining unit

The chemical composition of groundwater in the Amsden confining unit in the AYV was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in Appendix F3. The TDS concentration (1,360 mg/L) indicated that the water was slightly saline.

Concentrations of some properties and constituents in the Amsden confining unit in the AYV approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Water-quality analyses were available from only one produced-water sample, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in the produced-water sample and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable USEPA MCLs and HALs, so comparisons between sample concentrations and health-based standards could not be made. The produced-water sample had a concentration of one property (TDS) that exceeded aesthetic standards (USEPA SMCLs) for domestic use.

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the AYV. The produced-water sample had concentrations of two constituents (chloride and sulfate) that exceeded agricultural-use standards. No concentrations exceeded State of Wyoming livestock standards.

7.3.3.9 Madison aquifer

The chemical composition of groundwater in the Madison aquifer in the AYV was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations in the environmental water sample are listed in **Appendix E3**. The TDS concentration (138 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from the Madison aquifer in the AYV was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic,agriculture, or livestock water-quality standards.